

University of Southern Queensland  
Faculty of Health, Engineering and Sciences

# **Investigation of Energy Storage Media to Improve Network Voltage Regulation**

*A dissertation submitted by*  
**Heath A Camilleri**

*In fulfilment of the requirements of*  
**ENG4111/ENG4112 Research Project**

*Towards the degree of*  
**Bachelor of Engineering (Power)**

Submitted: October 2014

## **Abstract**

Ergon Energy currently has an extensive Single Line Earth Return (SWER) network across vast areas of regional Queensland. Growing load has caused many of these networks to approach their capacity limit. This leads to voltage fluctuations and usually requires expensive augmentation works.

If a portion of the load on these networks was transferred from the peak load period to a period of low demand, a more uniforming load curve would result. This would reduce the maximum demand of the line and negate the need for expensive augmentation works over long line lengths.

This project investigates pumped hydroelectric storage and SWER networks to gain a technical understanding of both technologies and their existing applications. It then analyses whether it is feasible to use pumped hydroelectric storage technology to negate the need for the line augmentation works described in the previous scenario. This feasibility is quantified by designing a pumped hydroelectric storage system and modelling its effect on an Ergon Energy SWER feeder.

The results show that it is technically possible to install a pumped hydroelectric storage scheme on a SWER feeder to improve voltage regulation and augment its capacity. However, a detailed study should be undertaken before undertaking such a project as it is only feasible where the additional civil infrastructure required for the scheme is minimal.

# **Limitations of Use**

**University of Southern Queensland**  
**Faculty of Health, Engineering and Sciences**  
**ENG4111/ENG4112 Research Project**

## **Limitations of Use**

The Council of the University of Southern Queensland, its Faculty of Health, Engineering & Sciences, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy or completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do so at their own risk, and not at the risk of the Council of the University of Southern Queensland, its Faculty of Health, Engineering & Sciences or the staff of the University of Southern Queensland.

This dissertation reports an educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled “Research Project” is to contribute to the overall education within the student’s chosen degree program. This document, the associated hardware, software, drawings, and other material set out in the associated appendices should not be used for any other purpose: if they are so used, it is entirely at the risk of the user.

---

**Professor Lyn Karstadt**

Executive Dean

Faculty of Health, Engineering and Sciences

## Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Heath A Camilleri

0019724018

---

Signature

---

Date



# Acknowledgements

I would like to acknowledge and thank:

Dr Leslie Bowtell – Faculty of Health, Engineering and Science, USQ.

My colleagues at Ergon Energy, with special mention of Mr Stephen Richards.

My wife Andrea and daughter Elisabeth.

Heath A Camilleri

University of Southern Queensland

October 2014

# Table of Contents

ABSTRACT	2
LIMITATIONS OF USE	3
CERTIFICATION	4
ACKNOWLEDGEMENTS	5
TABLE OF CONTENTS	6
LIST OF TABLES	12
LIST OF FIGURES	13
NOMENCLATURE	14
GLOSSARY	15
1. INTRODUCTION	16
1.1. Project Overview	16
1.2. Project Justification	16
1.3. Project Objectives	17

<b>2. LITERATURE REVIEW</b>	<b>18</b>
<b>2.1. Effects of Embedded Solar Generation of SWER Systems</b>	<b>18</b>
<b>2.2. Maximum Loadability of a SWER Network Using Energy Storage</b>	<b>19</b>
<b>2.3. Electrical Energy Storage Media Comparison</b>	<b>20</b>
2.3.1. Pumped Hydroelectric Storage (PHS)	21
2.3.2. Compressed Air Energy Storage (CAES)	21
2.3.3. Battery	22
2.3.4. Fuel Cell	25
2.3.5. Flow Battery	26
2.3.6. Solar fuels	27
2.3.7. Superconducting Magnetic Energy Storage (SMES)	28
2.3.8. Flywheel	28
2.3.9. Capacitor	28
2.3.10. Thermal Energy Storage (TES)	29
<b>2.4. Literature Review Conclusion</b>	<b>29</b>
<b>3. PROJECT INVESTIGATION - BACKGROUND INFORMATION</b>	<b>31</b>
<b>3.1. Hydroelectric Systems</b>	<b>31</b>
3.1.1. Overview	31
3.1.2. Pumped Hydroelectric Storage Systems	32
3.1.3. Existing Use of Pumped Hydroelectric Storage Schemes	33

<b>3.2.</b>	<b>Ergon Energy's Single Wire Earth Return Network</b>	<b>34</b>
3.2.1.	Overview	34
3.2.2.	Earth Return Principle	35
3.2.3.	Advantages	35
3.2.4.	Disadvantages	36
3.2.5.	Classification of SWER Networks	37
3.2.5.1.	Unisolated SWER	37
3.2.5.2.	Isolated SWER	37
3.2.6.	Ergon Energy's Common SWER Network Configurations	38
3.2.6.1.	Standard SWER – Common Configuration	38
3.2.6.2.	Standard SWER – 3 Phase Isolation Transformer Configuration	39
3.2.6.3.	Duplex and Triplex SWER	39
3.2.6.4.	Unisolated SWER	40
3.2.7.	Voltage Regulation Characteristics of SWER Networks	41
3.2.7.1.	Voltage Variation Limits	41
3.2.7.2.	The Ferranti Effect	42
3.2.7.3.	Unpredictable Load Curve	43
3.2.7.4.	Line Impedance	43
3.2.8.	Existing Solutions to Improving SWER Line Voltage Regulation	43
3.2.8.1.	Network Reconfiguration	44
3.2.8.2.	Augmentation of the Constrained Component	44
3.2.8.3.	Installation of Voltage Regulators	44
3.2.8.4.	Installation of a Grid Utility Support Systems (GUSS)	45
3.2.8.5.	Installation of Static Synchronous Compensator (STATCOM)	46
3.2.8.6.	Installation of Switched Reactors	47
3.2.8.7.	Installation of Embedded Fossil Fuel Powered Generation	47
3.2.8.8.	Implementation of a Demand Management Solution	47

<b>4.</b>	<b>DESIGN A PUMPED HYDROELECTRIC STORAGE PLANT</b>	<b>48</b>
<b>4.1.</b>	<b>Electrical Design Options Analysis</b>	<b>48</b>
4.1.1.	Conventional Synchronous Generator	48
4.1.2.	Brushless Synchronous Generator	48
4.1.3.	Asynchronous Generator	50
4.1.4.	DC Generator	50
4.1.5.	Permanent Magnet AC Generator	50
<b>4.2.</b>	<b>Electrical Design Overview</b>	<b>51</b>
4.2.1.	Modes of Operation	52
4.2.2.	Features	52
4.2.3.	Generator Design & Specifications	54
4.2.4.	Rectifier Design & Specifications	54
4.2.5.	Capacitor Design & Specifications	56
4.2.6.	Inverter Design & Specifications	57
4.2.7.	Controller Design & Specifications	57
4.2.8.	Generator Speed & Frequency Control	58
4.2.9.	Generator Voltage Control	58
4.2.10.	Inverter Power Control	59
4.2.11.	System Controls	61
4.2.12.	Network Undervoltage Response Sequence	62
<b>4.3.</b>	<b>Mechanical Design</b>	<b>62</b>
4.3.1.	Design Parameters	62
4.3.2.	Dam or Weir	63
4.3.3.	Instantaneous Flow	66
4.3.4.	Spillway	67
4.3.5.	Intake	68
4.3.6.	Penstock	69
4.3.7.	Turbine	70
4.3.7.1.	Turbine Classification	70
4.3.7.2.	Turbine Selection	71

<b>5. MODEL THE EFFECTS OF A PUMPED HYDROELECTRIC STORAGE PLANT ON AN ERGON ENERGY SWER FEEDER.</b>	<b>73</b>
5.1. Simulation Software Options	73
5.2. The Wambo Creek SWER	74
5.3. The Wambo Creek SWER Network PSS Sincal Model	75
5.4. Methodology	76
5.5. Results	77
5.6. Conclusions From Network Modelling	78
5.6.1. Assessment Against Key Performance Criteria	78
5.6.2. Active Power Vs Reactive Power Injection	79
<b>6. CONCLUSIONS &amp; RECOMMENDATIONS</b>	<b>80</b>
6.1. Achievement of the Project Objectives	80
6.2. Comparison With Other Storage Mediums	81
6.3. Effectiveness at Improving Network Voltage Constraints	81
6.4. System Design	81
6.5. Reservoir Requirements	81
6.6. Feasibility	82
6.7. Recommendations / Further Work	82

REFERENCES	83
APPENDIX A: PROJECT SPECIFICATION	86
APPENDIX B: BRUSHLESS GENERATOR DATA SHEET EXTRACT	87
APPENDIX C: BRIDGE RECTIFIER SPECIFICATIONS	89
APPENDIX D: CAPACITOR SPECIFICATIONS	90
APPENDIX E: MAGELLAN POWER INVERTER BROCHURE	92
APPENDIX F: RISK ASSESSMENT	94
APPENDIX G: SCHEMATIC DIAGRAM – WAMBO CREEK SWER	97
APPENDIX H: NETWORK MODELLING RESULTS – WAMBO CREEK SWER AT 100% LOAD WITHOUT PUMPED HYDROELECTRIC STORAGE	98
APPENDIX I: NETWORK MODELLING RESULTS – WAMBO CREEK SWER AT 100% LOAD WITH PUMPED HYDROELECTRIC STORAGE GENERATING 25 KVA	99
APPENDIX J: NETWORK MODELLING RESULTS – WAMBO CREEK SWER AT 25% LOAD WITHOUT PUMPED HYDROELECTRIC STORAGE	100
APPENDIX K: NETWORK MODELLING RESULTS – WAMBO CREEK SWER AT 25% LOAD WITH PUMPED HYDROELECTRIC STORAGE CONSUMING 25 KVA	101
APPENDIX L: NETWORK MODELLING RESULTS – WAMBO CREEK SWER AT 100% LOAD WITH PUMPED HYDROELECTRIC STORAGE GENERATING 25 KVAR	102
APPENDIX M: PROJECT SCHEDULE	103

## List of Tables

Table 1 -Technical Characteristics of Electrical Energy Storage Media (Chen, et al., 2009)	20
Table 2- Battery Storage Technology Risk Assessment (Helwig & Ahfock, 2013)	23
Table 3 - Battery Storage Technology Functionality (Helwig & Ahfock, 2013)	24
Table 4 - Battery Storage Technology Life Cycle Cost (Helwig & Ahfock, 2013)	24
Table 5 - Hydroelectric Scheme Head Height Classification	31
Table 6 - Hydroelectric Scheme Output Rating Classification	31
Table 7 - Ergon Energy's SWER Network Statistics (Ergon Energy SWER Improvement Group, 2012)	34
Table 8 - Voltage Variation across the Network at Constant Load	77
Table 9 - Voltage Variation Due to Varying Load at the Worst Case Node	77
Table 10 - Isolation Transformer Secondary Load Reduction Due to PHS	77
Table 11 - Active & Reactive Power Injection Comparison - Effect on Network Voltage	77



# List of Figures

Figure 1 – CAES Schematic Diagram (Chen, et al., 2009)	21
Figure 2 - ChangHong NF-S Nickel-Iron Battery Cycle life versus Depth of Discharge (Helwig & Ahfock, 2013)	25
Figure 3 - Flow Battery Schematic Diagram (SLAC National Accelerator Laboratory, 2013)	26
Figure 4 - Typical Pumped Hydroelectric Storage Scheme (Estrada, 2014)	32
Figure 5 - The Effects of a Pumped Hydroelectric Storage System on a Typical Load Curve (EIA, 2013)	33
Figure 6 - Ergon Energy's Standard SWER System Configuration	38
Figure 7 - Standard SWER with 3 Phase Isolation Transformer	39
Figure 8 – Ergon Energy's Standard Duplex SWER Configuration	40
Figure 9 – Ergon Energy's Common Unisolated SWER Network Configuration	41
Figure 10 - Permissible Network Overvoltage Limits (Australian Energy Market Commission, 2014)	42
Figure 11 - Connection Diagram of a Typical GUSS (Louis, 2013)	46
Figure 12 - Brushless DC Generator Configuration (Pearen, 2003)	49
Figure 13 - Pumped Hydroelectric Storage System Electrical Design	51
Figure 14 - Rectifier Output Waveform without Smoothing	55
Figure 15 – Generator Speed and Frequency Control Block Diagram	58
Figure 16 - Leroy Somer Shunt Type AVR Controller (Emerson, 2014)	59
Figure 17 – Generator Voltage Control Block Diagram	59
Figure 18 - Inverter Power Control Block Diagram	60
Figure 19 - Pumped Hydroelectric Storage System Control Block Diagram	61
Figure 20 – 25 kVA, 100 kWh PHS Mechanical Design Requirements	65
Figure 21 - Overflow Gravity Type Spillway (Penche, 1998)	67
Figure 22 - Hydroelectric Plant Intake Structures (Penche, 1998)	68
Figure 23 - Hydroelectric Plant Inlet Design	68
Figure 24 - Hydro Turbine Characteristics (Gilbert Gilkes & Gordon, 2014)	71
Figure 25 - Gilkes Compact Hydroelectric System Selection Chart (Gilbert Gilkes & Gordon, 2014)	72
Figure 26 - An Installed Gilkes Compact Hydroelectric System (Gilbert Gilkes & Gordon, 2014)	72
Figure 27 - PSS Sincal Diagrammatic Network Model Symbols	75
Figure 28 - Correct Workstation Setup (Ergonomics for Computer Workstation, 2014)	96

## Nomenclature

Term	Description	Units
AC	Alternating Current	
DC	Direct Current	
kV	kilo Volts	kV
kVA	kilo Volt Amperes	kVA
kW	Kilo Watts	kW
kWh	Kilo Watts hours	kWh
MWh	Mega Watt hours	MWh
m	Metres	m
m <sup>3</sup>	Cubic Metre	m <sup>3</sup>
pu	Per Unit	
var	Volt-ampere Reactive	var

## Glossary

AEMO	Australian Energy Market Operator.
EPCOS	A global company owned by TDK specialising in the manufacture of electronic devices.
Ergon Energy	Regional Queensland's electricity distribution network owner. A government owned corporation which supplies approximately 700,000 customers and 97% of the state's area.
Gilkes	Gilbert Gilkes & Gordon. An English based hydroelectric system and pump manufacturer.
GIS	Geographical Information System. A specialised computer system that stores, manipulates and displays geographical information.
Leroy Somer	A company specialising in industrial alternators and drive systems. Owned by Emerson Industrial Automation.
Magellan Power	An Australian AC and DC power systems company.
NEM	National Electricity Market.
PHS	Pumped Hydroelectric Storage.
PID Controller	Proportional - Integral - Derivative Controller. A controller that calculates the error between the measured process value and the desired setpoint. It attempts to minimise this error using the Proportional, Integral and Derivative control algorithms.
PLC	Programmable Logic Controller. A programmable plant controller which controls the plant from a centralised location.
Powerlink	Queensland's electricity transmission network owner. A government owned corporation.
PSS Sincal	Siemens proprietary network load flow and analysis software.
QCA	Queensland Competition Authority. The authority that sets electricity prices.
Recloser	A circuit breaking device used in high voltage substations and distribution lines. They have the capability of re-closing after a transient fault and are purchased complete with an enclosure containing all control and protection equipment.
SWER	Single Wire Earth Return Distribution Line Network.
Semikron	A global company specialising in the manufacture of power electronics systems and components.

# **1. Introduction**

## **1.1. Project Overview**

Ergon Energy currently has an extensive SWER network. It supplies approximately 26,000 customers across vast areas of regional Queensland. It is of significant national importance as it provides rural customers with an affordable energy supply. This affordable energy supply not only provides them with the comforts of modern technology, but allows their businesses and farms to be competitive in the global market that many of them sell to.

However, the load on these networks is steadily growing and many of these lines are reaching their capacity limit. Often, the first sign of this is voltage fluctuations which usually result in expensive augmentation works. The voltage fluctuations are often compounded by embedded solar and wind generation exporting excessive power during a period when this power is not being consumed in that part of the network.

The ultimate solution would be to install a storage system that can store energy during periods of low demand and high network voltage and release energy during periods of high demand and low network voltage. Ideally, the storage medium used would not lose capacity with depth of discharge or age. This would reduce ongoing maintenance costs and negate the need for augmentation works, resulting in a reduction in the cost of supplying electricity to these areas.

## **1.2. Project Justification**

The cost of electricity is dramatically increasing in Queensland. This was recently illustrated when the QCA set a 13% increase for July 2014, which followed a 22.6% increase for the previous year. These large price increases will cause significant financial, political and social ramifications for Queensland. With distribution costs making up 42% of the consumer's bill, distribution authorities must take every opportunity to decrease costs.

Augmenting SWER lines can be very expensive because of the long line lengths that are usually involved. For instance, upgrading a 10 km section of a 19.1 kV SWER network to a conventional three phase feeder costs in the order of eight million dollars. This is a large amount of capital, especially since the augmentation may only be required in order to supply a peak load for a small period of the day.

It is therefore imperative that new and innovative ways of increasing the peak capacity of SWER networks are developed. These alternatives will reduce upward pressure on electricity prices and are particularly important in Queensland because of the large scale of its SWER network.

### **1.3. Project Objectives**

The aim of this project is to assess whether it is practical to install a pumped hydroelectric storage scheme on an Ergon Energy SWER Line to improve voltage regulation.

Specifically, this project will:

1. Investigate electrical energy storage media and their suitability to the SWER network voltage regulation application.
2. Research background information relating to the design, construction and operation of hydroelectric systems.
3. Research background information relating to SWER networks.
4. Research background information relating to Ergon Energy's SWER network.
5. Analyse the current problems and conventional solutions employed to fix these problems within Ergon Energy's SWER network.
6. Design a pumped hydroelectric storage scheme for a typical rural application.
7. Model the effects of a pumped hydroelectric storage scheme on an Ergon Energy SWER feeder.
8. Analyse the results and determine whether it is feasible to implement a pumped hydroelectric storage scheme on a rural SWER line to improve network voltage regulation.

## 2. Literature Review

The research completed as part of this literature review aims to increase knowledge in the following areas:

- The effects of embedded solar generation on SWER network voltage regulation
- The factors that will help to achieve maximum benefit from an energy storage device installed on a SWER network
- The characteristics of battery storage technologies and the suitability of battery storage for SWER network voltage support
- The principle of operation of currently available energy storage technologies and an assessment of each energy storage medium's suitability for use for SWER network energy storage.

### 2.1. Effects of Embedded Solar Generation of SWER Systems

Guinane, Shafiuallah, Amanullah, & Harvey, 2012 modelled the effects of large-scale solar generation on three Ergon Energy SWER feeders. They concluded that due to their intermittent nature they caused a range of issues including voltage fluctuations, harmonics and power quality degradation.

The modelling covered three SWER lines with different characteristics; a large SWER network that had existing PV installations, a typical Ergon Energy SWER line and an unisolated SWER network (see section 3.2.5.1 for details). The modelling covered a range of scenarios from 0% PV penetration to 100% PV penetration. Analysis of the results from these scenarios showed that the higher the penetration of PV generation in the network, the worse was the effect on the network.

This paper highlighted the fact that although Ergon Energy's existing voltage regulation issues are improved by most forms of embedded network voltage regulation, because of its intermittent nature, embedded solar generation actually exacerbates the problem rather than improves it.

## **2.2. Maximum Loadability of a SWER Network Using Energy Storage**

Arefi & Ledwich, 2013 modelled an existing SWER line and ran an iterative process to optimise the location and size of batteries and regulators. The network studied was 140km long with a peak load of 284 kVA at the isolation transformer.

The modelling showed that 61% of peak load can be supplied by installing only 53.5 kVA of batteries when they are optimally located on the network. They found that for each installed kVA of batteries optimally located on the network the peak load on the network could be increased by 2 kVA. No voltage problems were observed when the batteries were in charging mode during off peak periods.

R.W.Jarrett, Maung Than Oo, & Harvey, 2012 modelled a GUSS and a RUSS unit on the Jericho North Ergon Energy SWER feeder in Western Queensland. The centralised approach was modelled. This consisted of a single GUSS unit, see Section 3.2.8.4 for details on these devices. The unit had a 25 kVA inverter with 100 kWh of battery storage. The decentralised approach was also modelled. This consisted of fifty-four RUSS units which had 6 kVA inverters coupled to 20 kWh of battery storage. RUSS units are similar to GUSS units but are designed for use on residential customers' premises. They are physically much smaller than GUSS units and can be connected directly to a customer's LV supply with minimal network modifications.

The study first modelled these inverters operating in "with battery" mode. This enabled them to operate in four quadrants by importing and exporting both real and reactive power. It was then compared with the inverters operating in 'without battery'. In this mode they only operated in two quadrants by importing and exporting only reactive power to stabilise the network voltage.

The system that was deemed to provide the most benefit to the network was the one that caused the least amount of additional power through the SWER isolating transformer while maintaining the voltage within acceptable limits. The results showed that the decentralised system was more effective at improving network voltage regulation in both with battery and without battery configurations. It also found that the four quadrant inverter provided more benefit to the network than the two quadrant inverter.

The study also found that multiple two quadrant devices controlled off network voltage sometimes actually increased power flow at the SWER isolation transformer and reduced the capacity of the network. In some cases this overloaded some components. It concluded that two quadrant devices required a centralised control system with numerous power and voltage measurements throughout the network.

## 2.3. Electrical Energy Storage Media Comparison

Chen, et al., 2009 investigated and compared the range of electrical energy storage media available. Table 1 summarises the characteristics of each storage medium studied.

Systems	Power rating and discharge time		Storage duration		Capital cost		
	Power rating	Discharge time	Self discharge per day	Suitable storage duration	\$/kW	\$/kWh	€/kWh-Per cycle
PHS	100–5000 MW	1–24 h+	Very small	Hours–months	600–2000	5–100	0.1–1.4
CAES	5–300 MW	1–24 h+	Small	Hours–months	400–800	2–50	2–4
Lead-acid	0–20 MW	Seconds–hours	0.1–0.3%	Minutes–days	300–600	200–400	20–100
NiCd	0–40 MW	Seconds–hours	0.2–0.6%	Minutes–days	500–1500	800–1500	20–100
NaS	50 kW–8 MW	Seconds–hours	~20%	Seconds–hours	1000–3000	300–500	8–20
ZEBRA	0–300 kW	Seconds–hours	~15%	Seconds–hours	150–300	100–200	5–10
Li-ion	0–100 kW	Minutes–hours	0.1–0.3%	Minutes–days	1200–4000	600–2500	15–100
Fuel cells	0–50 MW	Seconds–24 h+	Almost zero	Hours–months	10,000+		6000–20,000
Metal-Air	0–10 kW	Seconds–24 h+	Very small	Hours–months	100–250	10–60	
VRB	30 kW–3 MW	Seconds–10 h	Small	Hours–months	600–1500	150–1000	5–80
ZnBr	50 kW–2 MW	Seconds–10 h	Small	Hours–months	700–2500	150–1000	5–80
PSB	1–15 MW	Seconds–10 h	Small	Hours–months	700–2500	150–1000	5–80
Solar fuel	0–10 MW	1–24 h+	Almost zero	Hours–months	–	–	–
SMES	100 kW–10 MW	Milliseconds–8 s	1–15%	Minutes–hours	200–300	1000–10,000	
Flywheel	0–250 kW	Milliseconds–15 min	100%	Seconds–minutes	250–350	1000–5000	3–25
Capacitor	0–50 kW	Milliseconds – 60 min	40%	Seconds–hours	200–400	500–1000	
Super-capacitor	0–300 kW	Milliseconds – 60 min	20–40%	Seconds–hours	100–300	300–2000	2–20
AL-TES	0–5 MW	1–8 h	0.5%	Minutes–days		20–50	
CES	100 kW–300 MW	1–8 h	0.5–1.0%	Minutes–days	200–300	3–30	2–4
HT-TES	0–60 MW	1–24 h+	0.05–1.0%	Minutes–months		30–60	

Systems	Energy and power density				Life time and cycle life		Influence on environment	
	Wh/kg	W/kg	Wh/L	W/L	Life time (years)	Cycle life (cycles)	Influence	Description
PHS	0.5–1.5		0.5–1.5		40–60		Negative	Destruction of trees and green land for building the reservoirs
CAES	30–60		3–6	0.5–2.0	20–40		Negative	Emissions from combustion of natural gas
Lead-acid	30–50	75–300	50–80	10–400	5–15	500–1000	Negative	Toxic remains
NiCd	50–75	150–300	60–150		10–20	2000–2500		
NaS	150–240	150–230	150–250		10–15	2500		
ZEBRA	100–120	150–200	150–180	220–300	10–14	2500+		
Li-ion	75–200	150–315	200–500		5–15	1000–10,000+		
Fuel cell	800–10,000	500+	500–3000	500+	5–15	1000+	Negative	Remains and/or combustion of fossil fuel
Metal-Air	150–3000		500–10,000			100–300	Small	Little amount of remains
VRB	10–30		16–33		5–10	12,000+	Negative	Toxic remains
ZnBr	30 50		30 60		5 10	2000+		
PSB	–	–	–	–	10–15			
Solar fuel	800–100,000		500–10,000		–	–	Benign	Usage and storage of solar energy
SMES	0.5–5	500–2000	0.2–2.5	1000–4000	20+	100,000+	Negative	Strong magnetic fields
Flywheel	10–30	400–1500	20–80	1000–2000	~15	20,000+	Almost none	
Capacitor	0.05–5	~100,000	2–10	100,000+	~5	50,000+	Small	Little amount of remains
Super-			capacitor	2.5–15	500–5000			100,000+
20+		100,000+	Small	Little amount of remains				
AL-TES	80–120		80–120		10–20		Small	
CES	150–250	10–30	120–200		20–40		Positive	Removing contaminates during air liquefaction (Charge)
HT-TES	80–200		120–500		5–15		Small	

Table 1 -Technical Characteristics of Electrical Energy Storage Media (Chen, et al., 2009)



### 2.3.1. Pumped Hydroelectric Storage (PHS)

This technology is described in Section 3.1 and is widely used throughout the world. It can store large volumes of energy at a high efficiency and relatively low capital cost per unit of energy.

The major drawback of this technology is the difficulty in finding locations with two large reservoirs at different altitudes. The building of these plants requires a very long environmental approval lead time for the flooding of land if the reservoirs do not already exist.

### 2.3.2. Compressed Air Energy Storage (CAES)

This technology involves compressing air to a typical pressure of four to eight Mega Pascals. As shown in Figure 1, the air is pumped into an underground void surrounded by impervious material. These are most often made by mining activities or oil and gas extraction.

When electrical energy is required, the compressed air is heated and expanded through a high pressure turbine. The exhaust air from the high pressure turbine is then mixed with fuel and combusted through a low pressure turbine. Very high power ratings of hundreds of MVA can be achieved with this storage medium.

The major disadvantages of this technology is that it requires specific geological conditions to be viable and it requires the burning of fossil fuel to operate.

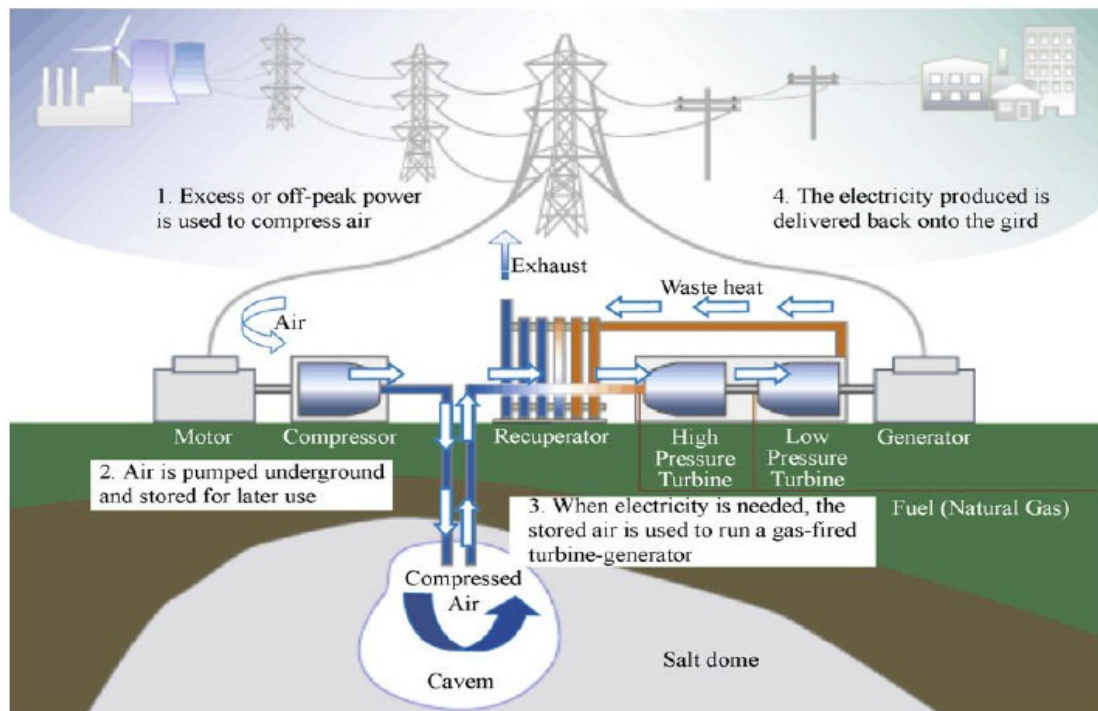


Figure 1 – CAES Schematic Diagram (Chen, et al., 2009)

### **2.3.3. Battery**

Batteries convert electrochemical energy into electrical energy with the entire process usually contained in a single enclosure. The chemical reaction is reversed during charging. Chen, et al., 2009 researched the characteristics of Lead Acid, Nickel Cadmium (NiCd), Sodium Sulphur (NaS), Sodium Nickel Chloride (Zebra) and Lithium-Ion (Li-ion) batteries.

Lead Acid Batteries are the oldest and most commonly used rechargeable batteries however their use for large applications is rare. They have an electrode of lead, metal and oxide submersed in an electrolyte of sulphuric acid. When discharged, the electrodes turns into lead sulphate and the sulphuric acid in the electrolyte becomes primarily water.

Helwig & Ahfock, 2013 compared Nickel-Iron batteries with other battery technologies. Their research specifically studied each battery type's suitability to use for SWER network voltage support application. The battery technologies compared were Lithium-Ion, Valve Regulated Lead Acid (VRLA), Nickel-Iron and Zinc-Bromide Redox Flow. The research focused on environmental and safety impacts, battery performance and life cycle costs.

## Environment and Safety

Table 2 summarises the results of the environment and safety risk assessment completed as part of the paper:

Risk Assessment Deep Discharge > 5kWh Storage Battery Bank Type				
Characteristic	Valve Regulated Lead Acid (VRLA)	Lithium-Ion	Nickel-iron (Edison pocket plate)	Zinc-Bromide Redox Flow
Fire ignition risk	<b>Minimal</b>	Thermal proximity to another fire source will cause internal thermal run-away	<b>Minimal</b>	<i>Electrolyte if heated may release toxic and highly corrosive hydrogen bromide and bromine fumes that will react directly with combustible materials causing their self ignition; with many organic compounds and hydrogen burn in bromine gas.</i>
Self-ignition risk	<b>Minimal</b>	<i>Thermal run-away due to overcharge, excessive charge rate in cold conditions, &gt;65°C temperature while charging. Thermal runaway can begin at 80°C, self combustion at 135°C.</i>	<b>Nil</b>	<b>Minimal</b>
Fire personnel fighting precaution requirements	Protection from acid burns and breathing apparatus to prevent fumes acid, lead/antimony/ arsenic dust/fumes from inhalation.	Full protection against explosion using full self-extinguishing fire suits and self powered self-contained breathing apparatus.	Face shield, breathing mask and body protection suit for protection against alkaline air borne mist.	<i>Bromine impervious facemask, neoprene based gloves and suit, special bromine proof respirator or self contained breathing apparatus. Safety shower after, and not to eat or drink until showered and full change of clothes.</i>
Fire Extinguishment requirements	<u>CO<sub>2</sub>, dry chemical or foam</u>	<b>Halon</b> , copper based, or powder based	<i>Secondary fire of battery container - use water, foam, BCF or powder type extinguishers.</i>	Neutralise with potassium carbonate solution, Cool surrounding areas with water to prevent thermal transfer to electrolyte. Use sand or vermiculite in a fire situation to safely absorb any liquid electrolyte.
Fire Extinguishment risks	Never use Water	<b>NEVER USE WATER, FOAM OR CO<sub>2</sub> DIRECTLY ON BURNING Li-ion batteries as these are combustible in the presence of lithium, adding to fire severity.</b>	<b>Nil</b>	<i>Do not use CO<sub>2</sub> or any organic based foam extinguishers if bromide (brown vapour) or hydrogen bromide are present from fire.</i>
Environmental hazards	<i>Lead, antimony and arsenic are toxic heavy metals in animals, marine life and insects.</i>	<i>Hydrogen Fluoride (HF) and fluorine based compounds from combustion of electrolyte are hazardous and damaging to the environment.</i>	<i>No long term hazard, localised immediate damage due to electrolyte alkalinity that can be quickly neutralised.</i>	<i>Zinc-bromide electrolyte is classed a long-term water based pollutant and is recognised toxic agent to marine and aquatic life.</i>
Persistence in environment	<i>Regulated waste due to heavy metal toxicity persistence.</i>	<i>Not established - under consideration at present due to presence of fluorine in electrolyte.</i>	<b>Nil</b>	
Human general risk	<i>Lead, antimony and arsenic are airborne / ingestible cancer agents, mutagens, and are highly toxic.</i>	<i>Lithium is a psychoactive agent, inhalation of combustion gases or ingestion are to be avoided by use of self contained breathing apparatus.</i>	<i>Nil to minor nickel allergy; Caustic mist from vented gas can cause lung irritation, eye damage if direct or skin irritation or burns.</i>	<i>Hydrogen bromide and bromine gas aggressively attack eye, skin, lung and internal body membranes.</i>
Human toxicity	<i>Lead inhalation or ingestion at sufficient levels is a neuro-toxin.</i>	<i>Fluorine based flame products from electrolyte combustion are destructively reactive to mucous membranes of eye, lungs and skin.</i>	<i>Nickel compounds are skin / lung irritants to approximately 10% of human population. Nickel toxicity is minimal, requiring ingestion of high doses of nickel based dust to act as a minor carcinogen agent.</i>	<i>Chronic toxicity affects include significant mental ability loss, slurred speech, poor memory, apathy, anorexia, drowsiness and sensitivity to touch and pain. Bromine is also a mutinogenic agent to bone marrow.</i>
Recycling legal requirements	<i>Heavy metal - reportable and traceable legal requirement.</i>	<i>Not established - currently under review due to presence of fluorine in electrolyte. Lithium ion batteries require traceability in recycling.</i>	<b>Nil</b>	<i>Zinc-bromide is a reportable and traceable marine and biological agent.</i>
Overall environmental and safety risk assessment.	<b>Medium to High</b>	<b>High</b>	<b>Low</b>	<b>Very High</b>
<b>KEY</b>	<b>Indicates nil or minimal hazard</b>			
	<i>Indicates hazard requires risk management</i>			
	<i>Indicates significant hazard requiring specific risk management responses</i>			
	<i>Indicates dangerous hazards requiring detailed risk assessment and hazard management in design, operation and disposal.</i>			

Table 2- Battery Storage Technology Risk Assessment (Helwig & Ahfock, 2013)

## Battery Performance

Table 3 summarises the results of the performance analysis completed as part of the paper:

Deep Discharge Storage Battery Type @ C(2hr) / C(3hr) Discharge Rates				
Characteristic	Gel/Glassmat VR Lead Acid	Lithium-Ion	Nickel-iron	Zinc-Bromide Redox
Open Circuit Cell Voltage	2.13	3.6 - 3.9 #	1.21 - 1.31 *	1.83
Turn around Efficiency high discharge rate	68%	75%	65%	68%
Cell Voltage at end of High Discharge Rate (C <sub>2hr</sub> ) - (C <sub>3hr</sub> )	1.65 (gel) 1.75(glassmat)	2.45	0.9	1.3
Turn around Efficiency low discharge rate (C <sub>2hr</sub> )	75%	90%	72%	72%
Cell Voltage at end of Low Discharge Rate	1.75 (gel) 1.85(glassmat)	2.75	1	1.3
Watt-hr. / kg	30	150	30	50 - 70
Cycle Life	250 - 1100 (gel)	1000 - 3000	2000 - 9000	2000 - 3000
	3000-4000 (glassmat)			
Recommended DoD	20 - 30% (gel)	30 - 65%	20 - 90%	20 - 85%
	40 - 70% (glassmat)			
DoD Memory Problems	nil	nil	nil	Nil
Withstand long periods @ low SoC	No	No	Yes	Yes
Suffers from Thermal Run-away	Yes	Yes	No	Needs Heat Exchanger
Maintenance Free	Yes	Yes	No	No
Max. Charge Rate	0.07 x Capacity	0.2 x Capacity	0.2 x Capacity	0.2 - 0.25 x Capacity
Tolerance to Over-charge	No Tolerance	No Tolerance	Very Good	Battery must disconnect when fully charged.
Optimal Depth of Discharge	10 - 30%	25 - 60%	20 - 90%	50 - 80%
Recommended Autonomy Period	To 4 months	To 6 months	14 days	6 months - year
Specific Fire Hazard	Thermal run-away; hydrogen venting necessary	Thermal run-away and self-ignition / explosion.	Hydrogen venting necessary.	Release of bromide
Personal Hazard	Acid electrolyte	Vented lithium gas/coumpounds and flourine gas.	Alkaline electrolyte	Bromide Gas
Environmental hazards	Heavy metal of lead		Almost nil	Bromide / Electrolyte
# depends on type of Lithium-Ion Battery				
* As these batteries accept and can store some overcharge - lower voltage is fully charged, upper voltage is retained overcharge voltage				
Indicates desirable characteristic				
Indicates mediocre characteristic				
Indicates non-desirable characteristic				

Table 3 - Battery Storage Technology Functionality (Helwig & Ahfock, 2013)

## Life Cycle Cost

Table 4 summarises the results of the life cycle cost analysis completed as part of the paper:

Battery Type	Adv. VRLA	Nickel-Iron	Lithium-Ion	Zinc-Bromide
10 year life	\$1,000	\$840	\$700	\$1,060
20 year life	\$1,200	\$720	\$630	\$800
30 year life	\$1,366	\$840	\$1,100	\$1,146

Table 4 - Battery Storage Technology Life Cycle Cost (Helwig & Ahfock, 2013)

It can be seen in the above tables that Nickel-Iron batteries consistently perform better than the other battery technologies against most criteria. The paper concludes that Nickel-Iron batteries are a good choice for SWER line voltage support where the space footprint is not an issue.

Note the Recommended DOD (Depth of Discharge) row of Table 3. Every battery type has a recommended depth of discharge and discharging a battery beyond this point will excessively shorten the battery's life. The depth of discharge curve for a ChangHong Lithium-Ion battery is shown in Figure 2. It shows a gradual decrease in the cycle life expectancy of these batteries as the depth of discharge is increased. This is a major disadvantage of any type of battery technology.

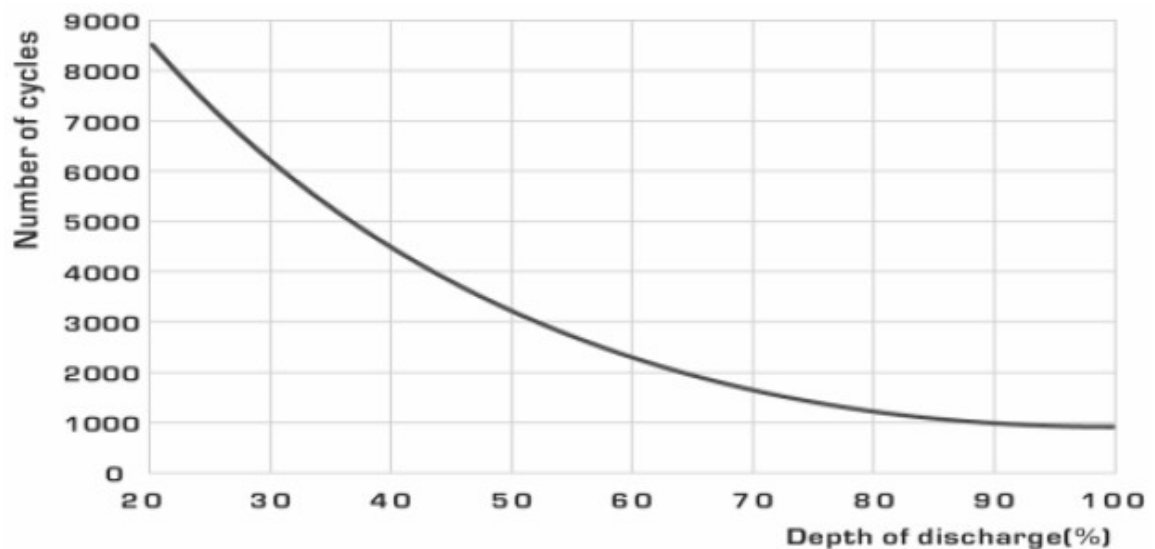


Figure 2 - ChangHong NF-S Nickel-Iron Battery Cycle life versus Depth of Discharge (Helwig & Ahfock, 2013)

Batteries have a high energy efficiency of 60-90% and can be purchased with very short lead times. As shown in Table 1, some criteria vary depending on what type of battery is used. The installation of battery technology is convenient as it is an “off the shelf” item that requires very little engineering design changes when installing it at different locations in the network. However, the more the battery capacity that is used, the shorter their cycle life expectancy is and the higher the cost of using them for voltage regulation on a SWER network becomes.

#### 2.3.4. Fuel Cell

Fuel cells are devices that convert electrochemical energy to electrical energy. They consume reactants which must continually be replaced in contrast to batteries which store their reactants in a closed system. This allows them to operate continuously if the flow of reactants is maintained. Reversible fuel cells are able to convert electrical energy into chemical energy.



Chen, et al., 2009 researched Hydrogen, Direct Methanol, Molten Carbonate, Solid Oxide and the Metal-Air Battery fuel cell technologies. The most common of those researched is the hydrogen fuel cell which uses hydrogen and oxygen to produce electricity and water. They comprise of an electrolyser unit which converts the input electricity into hydrogen, the hydrogen storage and the energy conversion system that converts the chemical energy back to electrical energy. As described in the paper, there are a number of methods available for achieving these conversions.

The main advantages of fuel cell technology is its high energy storage density and long storage duration, however they require high capital costs to install.

### 2.3.5. Flow Battery

As shown in Figure 3, the flow battery utilises externally stored electrolyte solutions that flow through a reactor to convert chemical energy to electrical energy. The storage capacity of this technology is only limited by the size of the electrolyte storage tanks. The power rating is determined by the active area of the cell stack. The chemical reaction of most flow battery installations is reversible. The entire electrolyte in a flow battery flows through the reactor in contrast to a fuel cell where only the electro-active chemicals flow through the reactor.

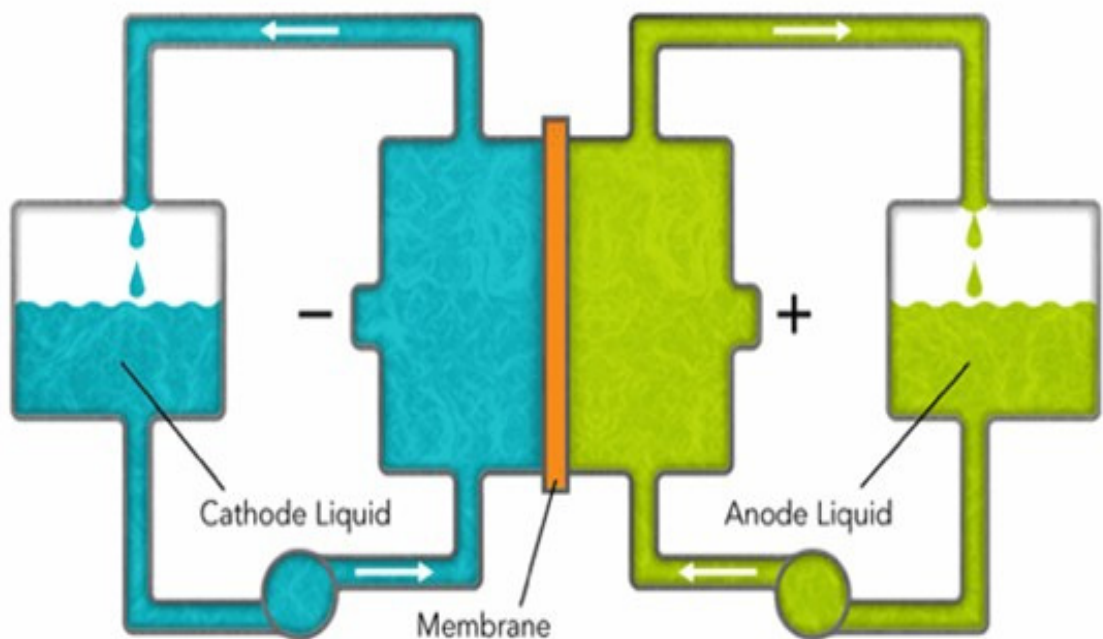


Figure 3 - Flow Battery Schematic Diagram (SLAC National Accelerator Laboratory, 2013)

Chen, et al., 2009 researched the Vanadium Redox Flow Battery (VRB), the Zinc Bromine Battery (ZnBr) and the Polysulphide Bromide Flow Battery (PSB). For example, the Vanadium Redox Battery (VRB) comprises of  $V^{2+}/V^{3+}$  redox couples stored in mild sulphuric acid in the negative half-cell and  $V^{4+}/V^{5+}$  redox couples stored in mild sulphuric acid in the positive half-cell. During charge/discharge,  $H^+$  ions are exchanged through the hydrogen-ion permeable polymer membrane.

Flow batteries have been constructed with a power rating of up to 5 MW and have a longer cycle life than conventional batteries. However they are more complex than conventional batteries as they require pumps to move the electrolyte through the reactor. They are not as readily available as other technologies and the additional plant requirements gives them a lower power density than conventional batteries.

#### **2.3.6. Solar fuels**

Solar fuel systems operate by concentrating sunlight over a small area using parabolic mirrors. The sunlight is concentrated onto receivers and reactors where an endothermic chemical reaction takes place at high temperature. The substance can then be stored, transported and converted into electricity as required.

Chen, et al., 2009 researched Solar Hydrogen, Solar Metal and Solar Chemical Heat Pipe technologies. For example, the Solar Hydrogen technology involves producing hydrogen from water using sunlight. Because the conversion of energy from sunlight into an energy storage medium is part of the generation process, unlike other systems, the efficiency of the system is not impacted when the storage is actually used.

Solar fuel technology is environmentally friendly and is suitable for storing energy for many months. However it requires sunlight to operate and is a new technology that is not readily available yet.

### **2.3.7. Superconducting Magnetic Energy Storage (SMES)**

SMES operates by storing electrical energy as direct electric current passing through a coil made from circular superconductor material. The coil is immersed in liquid helium contained in a vacuum insulated cryostat and kept at a very low temperature so that it stays in a superconducting state.

SMES can have a power rating of one to ten megawatts and stores energy with a very high efficiency (approximately 97%). SMES also has a very large cycle life. However this technology can only store energy for short periods of time which makes it unsuitable for the SWER network voltage regulation application.

### **2.3.8. Flywheel**

The flywheel operates by storing energy in a rotating mass. The mass is spun by a motor when charged. During Discharge, the momentum from the rotating mass spins the motor which acts as a generator. The amount of energy that is stored depends on the flywheel's size and its speed of rotation. Flywheels have been used for many thousands of years, but modern flywheels have features such as very low resistance bearings and are contained in a vacuum to reduce losses.

Flywheels have a long life and high efficiency when compared to other storage media. However they are only able to discharge power over a short duration (maximum 30 seconds). This makes them ideal for use as a power quality device to provide ride-through capability for short duration power interruptions, but unsuitable for the SWER network voltage support application.

### **2.3.9. Capacitor**

A Capacitor consists of two metal plates separated by a dielectric material. In super-capacitors, this solid dielectric material is replaced with a liquid. Super-capacitors often have electrodes made of porous carbon or other high surface area material. Porous carbon has a surface area of up to 2000 m<sup>2</sup> per gram and with typical distances between plates of less than 1nm, very large capacitances and quantities of stored energy can be achieved.

Capacitors / Super-Capacitors have a very high cycle life, however their short storage duration and short discharge time (maximum 60 minutes) makes them unsuitable for the SWER network voltage support application.



### **2.3.10. Thermal Energy Storage (TES)**

Thermal Energy Storage works by heating or cooling a material and storing it in an insulated container. The material can then be recovered for electricity generation using heat engine cycles.

Chen, et al., 2009 researched High Temperature (HT-TES), Cryogenic Energy Storage (CES) and Low Temperature TES (LT TES). For example, Cryogenic Energy Storage stores energy by generating Cryogen (e.g. liquid nitrogen). It then releases energy by using the heat from the surrounding environment to boil the liquid which powers a Cryogen heat engine.

Thermal Energy Storage has a low capital cost per unit of energy, is benign to the environment and has a relatively long storage medium. However it has a relatively low efficiency.

## **2.4. Literature Review Conclusion**

The following conclusions can be made with regard to SWER network voltage regulation:

- Embedded solar generation exacerbates network voltage regulation issues on SWER feeders rather than improving them.
- The placement of the energy storage device on the SWER feeder shall be analysed to gain maximum benefit.
- With correct placement of the energy storage device, the capacity improvement that will be achieved on the SWER network should exceed the power injected into the network. This will be an indicator of successful placement and modelling of the device.
- Installing a four quadrant device on a SWER feeder will yield greater benefit than installing a two quadrant device.
- A four quadrant device placed on a SWER line to improve network voltage regulation can be effectively controlled directly from network voltage.

The following conclusions can be made with regard to possible energy storage media for the SWER network voltage regulation application:

- Flywheels and Capacitors are not suitable for network voltage support because of the short storage duration.
- Batteries are not ideal for the network voltage support application because of their short life expectancy. Also, the more the battery capacity that is used, the smaller their

cycle life expectancy is which increases the cost of using them. If battery technology was chosen for the network voltage support application, Nickel-Iron batteries would be the preferred battery type.

- Flow Batteries have a larger cycle life when compared to conventional batteries but their complexity makes them not ideal for the typically remote SWER line locations. A conventional Nickel-Iron battery would be preferred to a Flow Battery for the SWER network voltage support application.
- CAES is unsuitable for the SWER network voltage support application because the technology is only feasible for plants of more than 5 MW.
- Solar Fuel and Fuel Cell technologies are new technologies that are not commercially available yet. They have therefore been deemed unsuitable for the SWER network voltage support application at this stage.
- Thermal energy storage technologies such as CES are not preferred for the network voltage support application because this technology is still under development and the process developed to date has a low efficiency.
- Pumped hydroelectric storage is an excellent storage technology because it is a reliable, commercially available technology which has a high efficiency and is capable of storing energy for a long duration. Its capacity does not decline with age, the number of times it is cycled or the depth to which it is discharged. Pumped hydroelectric storage technology has not yet been used on a small scale to improve network voltage regulation, however if the water reservoirs required are available, this technology is superior to the other technologies studied. The remainder of this project will therefore focus on the installation of a pumped hydroelectric storage scheme to improve the voltage regulation on a SWER feeder.

## 3. Project Investigation - Background Information

### 3.1. Hydroelectric Systems

#### 3.1.1. Overview

A hydroelectric system converts gravitational potential energy contained in water at a height into electrical energy.

There are two types, reservoir schemes and run of the river schemes. Reservoir schemes have a large reservoir that is able to regulate the flow of water to the turbines. The reservoir is large enough to smooth out natural flow variations in the river. It requires building a dam and flooding large areas of land.

Run of the river scheme do not have any water storage capability and are subject to seasonal and daily variations in the amount of water flowing down the river. They create less environmental and social impacts because, although a small dam is often built for these systems, the dam will not be large enough to cause flooding of large areas.

Both run of the river and dammed reservoir schemes can be of any head height and any size.

Hydroelectric systems are also be classified according to their head height and maximum output rating as illustrated in Table 5 and Table 6.

Head Height	Classification
2 – 30 m	Low Head
30 – 100 m	Medium Head
More Than 100 m	High Head

*Table 5 - Hydroelectric Scheme Head Height Classification*

Maximum Output Rating	Classification
Less Than 100 kW	Micro
100 – 1000 kW	Mini
1 MW – 10 MW	Small
10 MW – 300 MW	Medium
Larger Than 300 MW	Large

*Table 6 - Hydroelectric Scheme Output Rating Classification*

### 3.1.2. Pumped Hydroelectric Storage Systems

As illustrated in Figure 4, pumped hydroelectric storage schemes operate in two cycles:

Generation Cycle: The plant operates as a hydroelectric generator, converting the stored gravitational potential energy in its high level water reservoir into electrical energy.

Pumping Cycle: The plants turbine is reversed, its generator acts as a motor, taking energy from the electricity network. It pumps water from the lower reservoir to the upper reservoir.

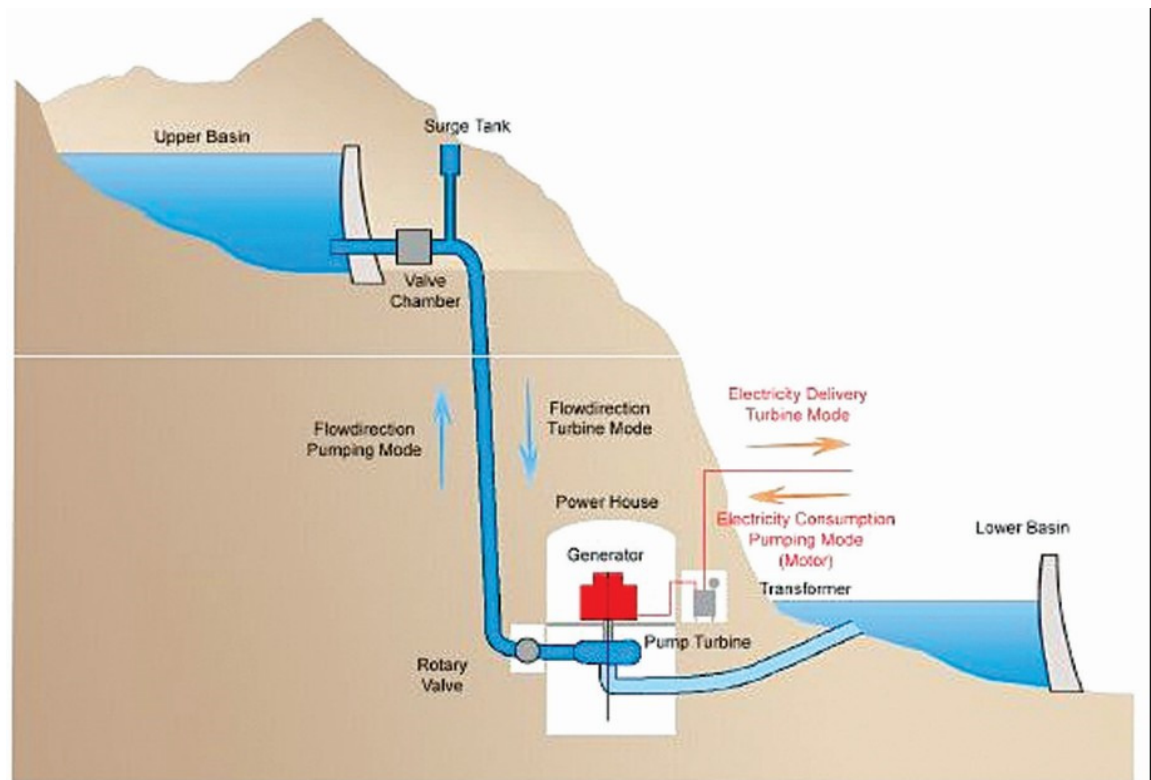


Figure 4 - Typical Pumped Hydroelectric Storage Scheme (Estrada, 2014)

Pumped hydroelectric storage schemes generally have little or no inflow to their upper reservoir. They act as an energy storage device, storing energy during times of low demand and releasing this energy during times of high demand.

### 3.1.3. Existing Use of Pumped Hydroelectric Storage Schemes

Located approximately 90 Km north-west of Brisbane, Wivenhoe Power Station is an example of a pumped hydroelectric storage power plant currently operating in the Queensland electricity network. The capacity of its upper storage allows its two 250 MW units to generate continuously at full load for up to 10 hours.

The generators are connected via step-up transformers directly to the NEM via Powerlink's 275kV transmission line network. The price that the power station buys and sells its energy is determined by the supply and demand available in the market at the time. This "spot price" is determined in five minute intervals and averaged every half hour.

Generally this sees the scheme operate as a generator during the morning and afternoon peaks and operate as a pump during the night. It takes approximately 14 hours for the units to pump enough water from the lower reservoir to its upper reservoir to fill it to its full capacity.

As with any energy storage device, there are efficiency losses associated with both the charge and discharge cycles. In other words, in total, pumped hydroelectric storage schemes consume more energy than they produce. Therefore, there must be an adequate difference between the price of energy during generation and pumping periods for a pumped hydroelectric storage system to be economically viable. Figure 5 shows the effects of a pumped hydroelectric storage scheme on a typical daily load curve and the typical net electricity generated by a pumped hydroelectric storage scheme.

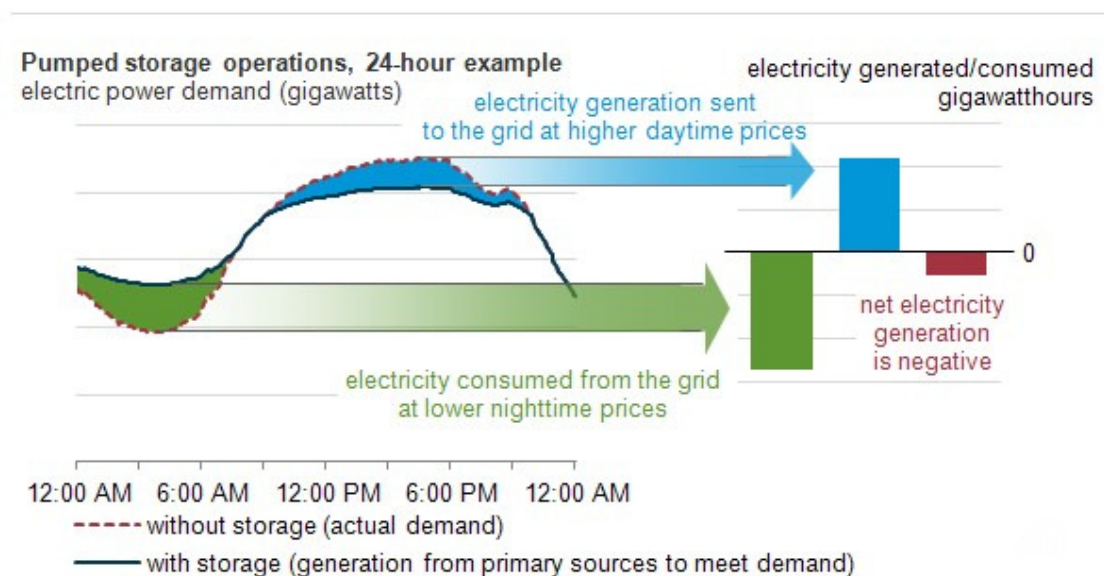


Figure 5 - The Effects of a Pumped Hydroelectric Storage System on a Typical Load Curve (EIA, 2013)

It is quite common to utilise pumped hydroelectric storage technology on large scale transmission networks. These systems are economically viable because of the well-established market and pricing structures that are in place. The large scale of these projects make it viable to spend large amounts of capital on installing civil infrastructure such as dams and tunnels. However, the research conducted as part of this project has not been unable to find a single instance where a small scale pumped hydroelectric storage scheme has been installed on a SWER network to improve voltage regulation.

## 3.2. Ergon Energy's Single Wire Earth Return Network

### 3.2.1. Overview

Ergon Energy currently has an extensive SWER network. It supplies approximately 26,000 customers across a large area, with a very low load density. The average length of an Ergon Energy SWER line is 80 km. Table 1 gives a statistical overview highlighting the sheer magnitude of the network.

Asset or Indicator	Description	Value	
Customers	Number	25,322	
	Density	2.53	km/customer
	Annual growth	3.8%	
SWER Network	Total Schemes	758	
	Unisolated	98	12.9%
Conductor	Length	64,000	km
	% of Network	43%	
Voltage	11kV	70	
	12.7kV	421	
	19.1kV	267	
Isolating Transformers	Number	651	
	Installed Capacity	96.4	MVA
	Utilisation	77.9%	
SWER Transformers	Number	24,973	
	Installed Capacity	249.9	MVA
	Annual Growth	2.4%	
	Density	3.9	kVA/km

Table 7 - Ergon Energy's SWER Network Statistics (Ergon Energy SWER Improvement Group, 2012)

### 3.2.2. Earth Return Principle

All SWER line configurations utilise the Earth for the current's return path. The resistance of this path is greatest closest to the earth electrode where all the current has to flow through a small area of soil. As the current moves away from the electrode, the current disperses and the cross-sectional area of soil that it travels through increases thus reducing the resistance of the return path.

The alternating current would disperse into an infinitely wide area of soil resulting in a zero resistance return path if it were not for the fact that the capacitive reactance of a line increases proportional to the mean distance between the forward and return electron paths. Keeping in mind that capacitance is inversely proportional to the distance between the conductors in accordance with Equation 1.

*Equation 1:*

$$X_c = \frac{1}{2\pi fC}$$

Where  $X_c$  = Capacitive Reactance,  $C$  = Capacitance,  $f$  = frequency

The current flow therefore finds the lowest impedance path which is a compromise between dispersing which will minimise resistance and reducing its distance to the overhead active conductor which will minimise reactance.

A typical SWER line will see a mean current path of 1500m below the surface producing a return path resistivity of 0.034  $\Omega$ /km.

### 3.2.3. Advantages

SWER networks are used in rural applications where there is a small load spread over a large area. They have the following advantages when compared to conventional networks:

#### Cost:

The installation of a SWER line requires a much lower capital cost than the installation of a conventional feeder. This is because less conductor and a narrower land easement is required. The number of switching and protection devices required is lower for a SWER network. Also, line design and construction is simpler and faster as there is no need to be concerned with phase to phase clearances.

#### Reduced Maintenance

SWER lines require less maintenance than conventional networks due to the reduced amount of components in the network.

#### Electrical Separation

SWER feeder isolation transformers provide a degree of electrical separation between the SWER network and the conventional network it is connected to. This makes it unlikely that a fault on the SWER line will affect the rest of the network. This is particularly important for typical SWER line applications which involve very long distances, increasing the exposure of the electrical distribution network to the environmental factors which cause faults.

#### Metering

Metering of a SWER network can be easily performed by inserting a low voltage meter on the earth cable of a SWER substation. If a temporary measurement is required, this can be done with a clamp-on style ammeter. A similar operation on a conventional network would require isolation of the network to allow safe access to the live overhead conductors and working at heights procedures would have to be followed.

### **3.2.4. Disadvantages**

SWER networks have the following disadvantages when compared to conventional networks:

#### Interference with Telephone Lines

The earth currents produced by SWER networks cause interference with nearby telephone lines. A minimum of 80 metres clearance must be maintained between power lines and telephone lines to avoid this issue.

#### Limited Capacity

The active conductor of a SWER line has a maximum economically viable size due to the high reactance of the earth return circuit. Therefore, the maximum load that can be delivered by a SWER line is much smaller than a conventional distribution line.

#### Three Phase Load Balancing

SWER is a single phase network, it therefore causes unbalance in the three phase plant that supplies it. Unbalanced load can lead to voltage unbalance on distribution feeders which can damage the three phase equipment connected to it. One method of correcting this unbalance is by supplying three separate SWER lines off the same three phase supply point.



### **3.2.5. Classification of SWER Networks**

#### **3.2.5.1. Unisolated SWER**

The load on an unisolated SWER network appears as an earth return current on the secondary side of the zone substation transformer. They utilise a single phase to ground SWER transformer which is supplied directly from the zone substation. Unisolated SWER networks can be converted to isolated SWER networks by either:

- 1) Converting the SWER transformer to a two phase transformer supplied from a two phase line
- 2) Installing a three phase delta to star isolation transformer on the line supplying the unisolated SWER network.

Unisolated SWER networks were often installed in Queensland's regional electricity distribution network in the 1970's. However, this type of SWER network is currently being phased out across Ergon Energy for the following reasons:

- They draw a single phase current which draws an unbalanced load at the zone substation power transformer.
- They generate unwanted neutral currents in the star-point to earth connection of the zone substation power transformer. This means that Sensitive Earth Fault (SEF) protection cannot be utilised on the feeder supplying the SWER line which therefore poses a safety and security of supply risk to the line.

#### **3.2.5.2. Isolated SWER**

An Isolated SWER network is distinguished by the fact that the earth return current does not flow through the star point to earth connection of the transformer in the zone substation. The earth current is only present beyond the isolation transformer or the two phase SWER transformer. This type of network does not have the disadvantages of the unisolated SWER network detailed previously.

### 3.2.6. Ergon Energy's Common SWER Network Configurations

#### 3.2.6.1. Standard SWER – Common Configuration

Figure 6 shows Ergon Energy's standard SWER line configuration which is used extensively throughout the network. This configuration is classified as an isolated SWER network.

The Conventional Feeder is protection by overcurrent, earth fault and sensitive earth fault relays at the zone substation. The SWER isolation transformer is protected by its HV fuses. The SWER line is protected by the single phase recloser at the source end of the line. The customer LV supply transformers are protected by their HV fuses.

The settings of each protection device are designed to provide delayed backup protection to the downstream protection. However, the earth fault and sensitive earth fault protection are unable to detect earth faults on the SWER network as these are converted to line currents by the SWER isolation transformer.

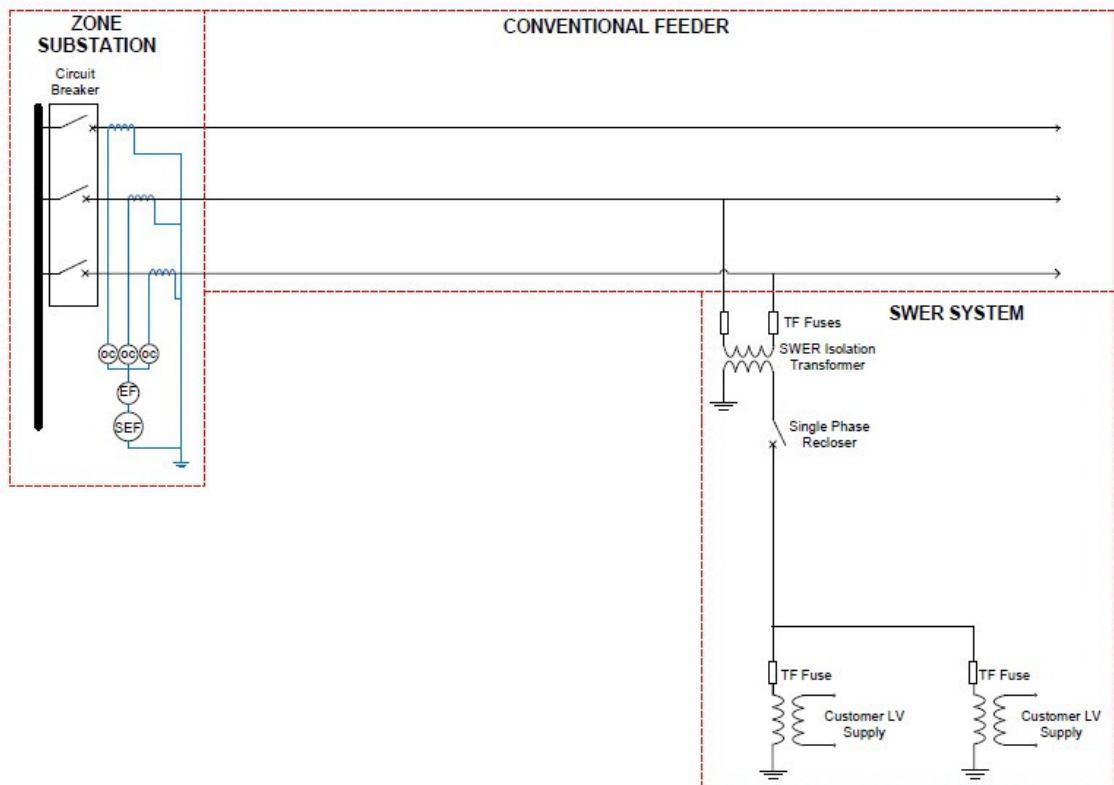


Figure 6 - Ergon Energy's Standard SWER System Configuration

### 3.2.6.2. Standard SWER – 3 Phase Isolation Transformer Configuration

Figure 7 shows an Ergon Energy standard SWER line configuration which is occasionally used throughout the network. This configuration is used where there are three SWER lines radiating from a substation. It is an isolated SWER network.

The protection works in the same manner that was described in Section 3.2.6.1 however the conventional feeder portion is often limited to an underground cable supplying the SWER isolation transformer in the zone substation.

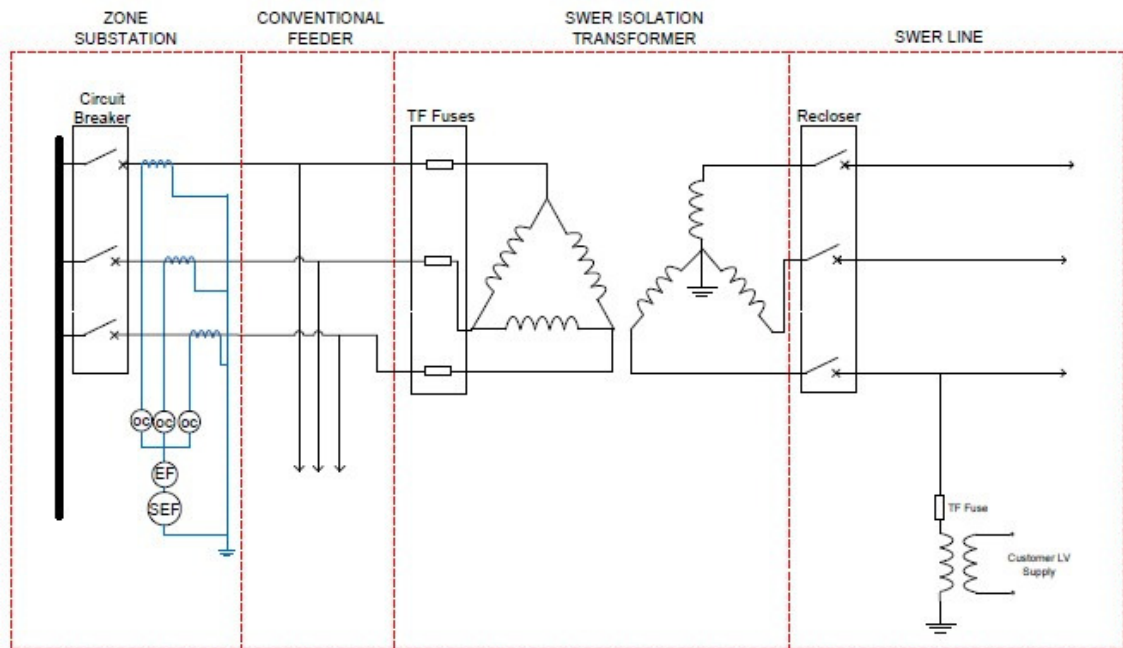


Figure 7 - Standard SWER with 3 Phase Isolation Transformer

### 3.2.6.3. Duplex and Triplex SWER

Figure 8 shows Ergon Energy's standard duplex SWER line configuration which is commonly used throughout the network. This configuration is classified as an isolated SWER network. The protection works in the same manner that was described in Section 3.2.6.1.

Duplex SWER lines can be a cost effective solution as they utilise a common pole to mount the apparatus for what is effectively two separate SWER networks with double the capacity of a conventional SWER network.

A triplex network is similar to the duplex network except it is effectively three separate SWER networks instead of two. A Triplex SWER network is able to triple the capacity of a conventional SWER network.

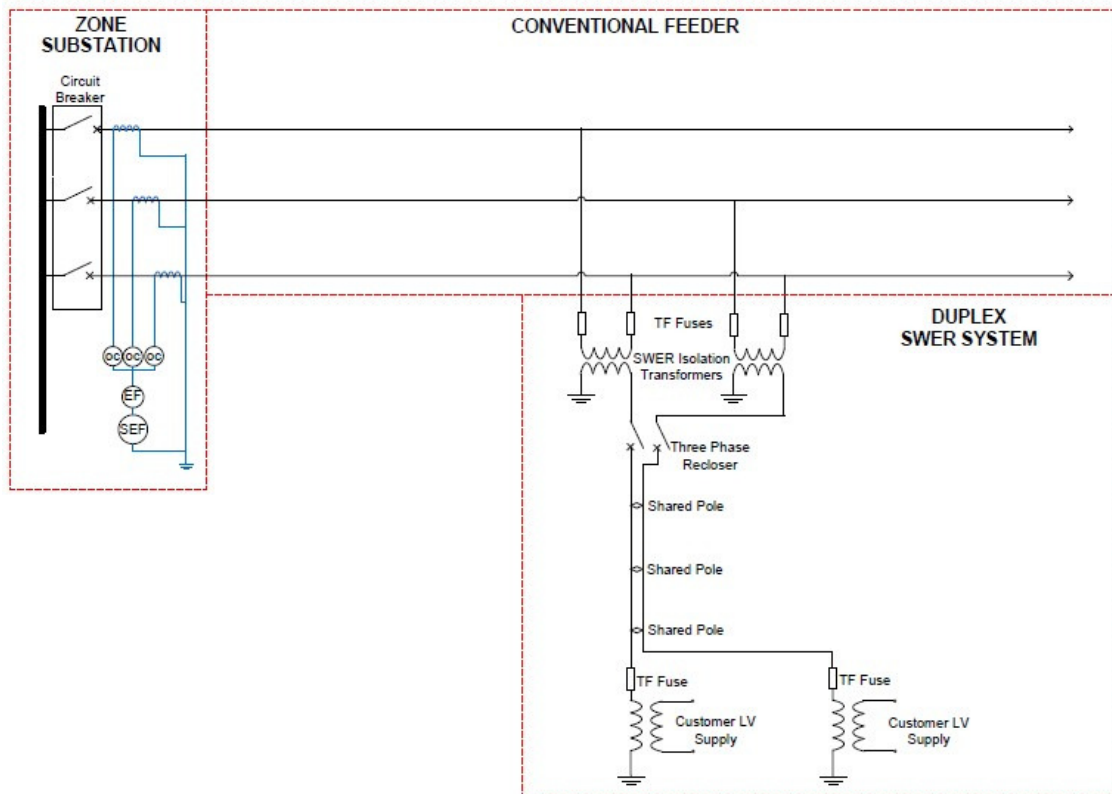


Figure 8 – Ergon Energy's Standard Duplex SWER Configuration

#### 3.2.6.4. Unisolated SWER

Figure 9 shows Ergon Energy's unisolated SWER network configuration which was often installed in Queensland's regional electricity distribution network in the 1970's. This type of SWER network is described in Section 3.2.5.1 and is currently being phased out across Ergon Energy.

The protection works in the same manner that was described in Section 3.2.6.1 however sensitive earth fault protection cannot be implemented on such a network because of the high earth return current on the star-point to earth connection of the zone substation power transformer.

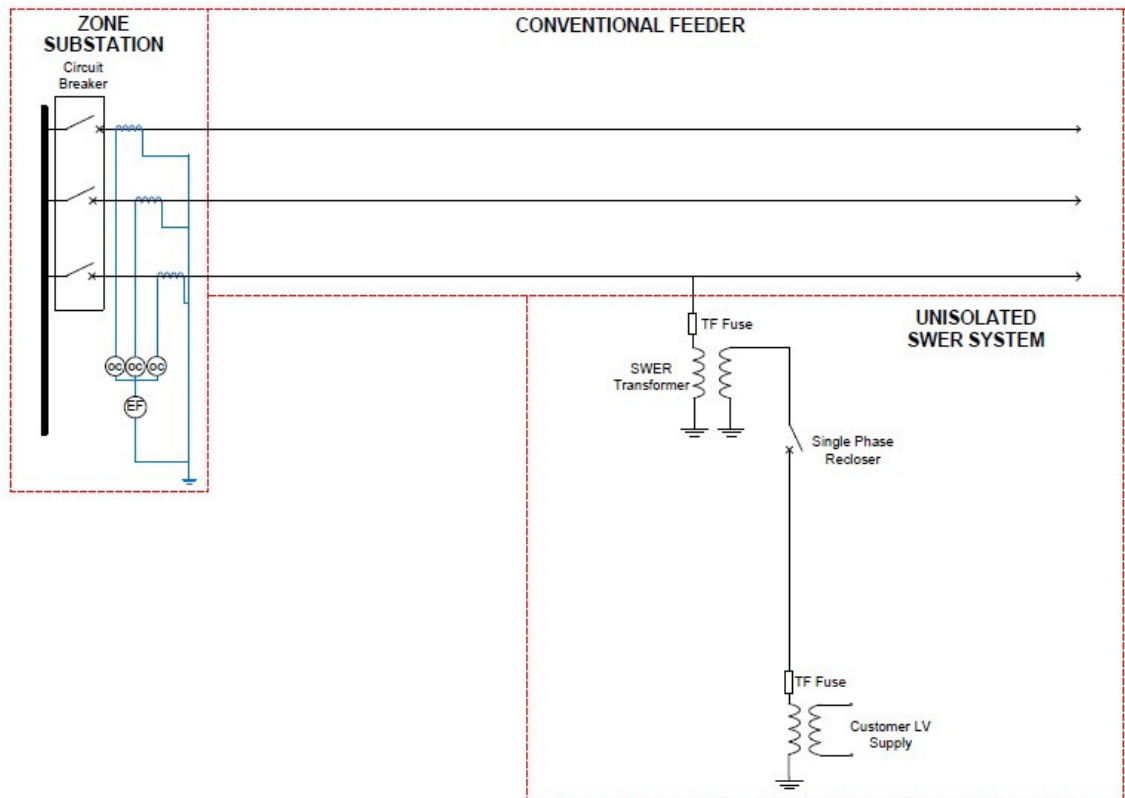


Figure 9 – Ergon Energy's Common Unisolated SWER Network Configuration

### 3.2.7. Voltage Regulation Characteristics of SWER Networks

#### 3.2.7.1. Voltage Variation Limits

Section S5.1a.4 of the national electricity rules state the following:

*Except as a consequence of a credible contingency event, the voltage of supply at a connection point should not vary by more than 10 percent above or below its normal voltage, provided that the reactive power flow and the power factor at the connection point is within the corresponding limits set out in the connection agreement.*

*As a consequence of a credible contingency event, the voltage of supply at a connection point should not rise above its normal voltage by more than a given percentage of normal voltage for longer than the period shown in Figure S5.1a.1.*

*As a consequence of a credible contingency event, the voltage of supply at a connection point could fall to zero for any period.*

Figure S5.1a.1 referred to in the above text is shown in Figure 10. This Section of the national electricity rules clearly defines the criteria that must be met by the network under normal and fault conditions. This is essential when assessing the effectiveness of any voltage regulation improvement or augmentation project.

Note that in accordance with the above rules, the voltage is assessed at the customers' network connection point. This means that network voltages can be adjusted beyond these limits, as long as the customer's voltage limits are maintained at their connection point.

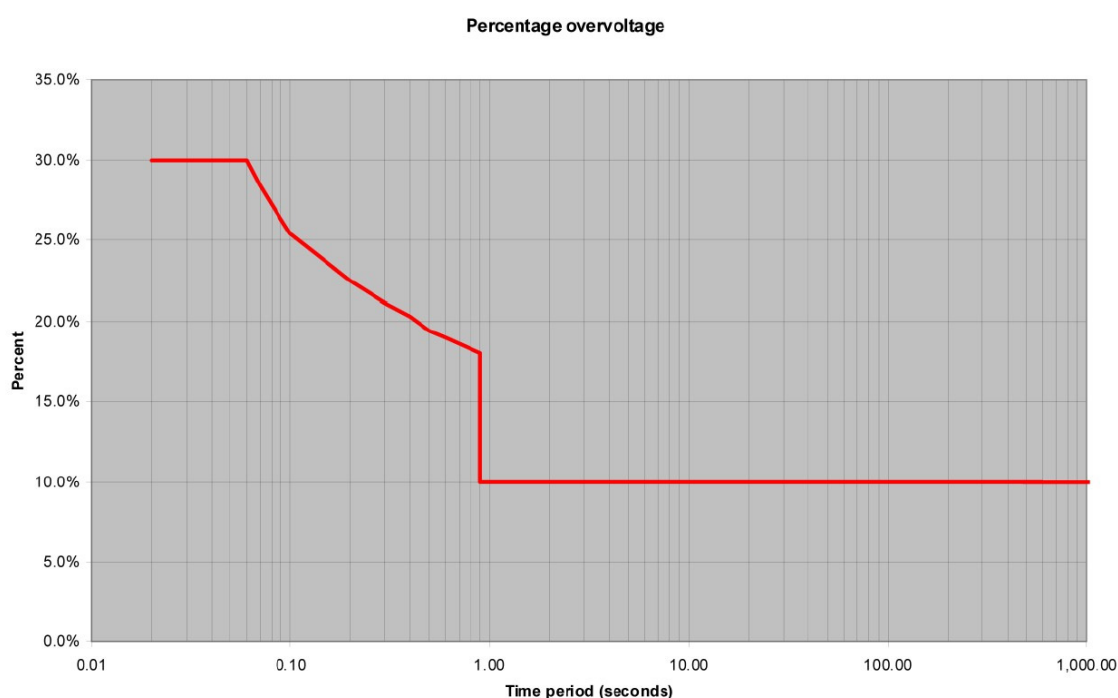


Figure 10 - Permissible Network Overvoltage Limits (Australian Energy Market Commission, 2014)

### 3.2.7.2. The Ferranti Effect

This phenomena occurs on lightly loaded long power lines and becomes evident when the voltage at the end of the line is higher than the voltage at the source. It occurs when the capacitive current produces a voltage drop across the line inductance that is in-phase with the sending end voltage.

It is prevalent in SWER lines because of their long line lengths and smaller loads and can be especially dangerous, producing overvoltage conditions when a large Section of line is disconnected after a fault. Surge arrestors are installed on the network to limit the effects of these overvoltage conditions after a fault.

### **3.2.7.3. Unpredictable Load Curve**

Because SWER networks are used for applications where low load density is spread over a very large area, parts of the network have limited Diversity. This means that the timing and duration of periods with high and low consumption are difficult to predict. This in turn makes the timing of voltage peaks and troughs difficult to predict.

This has implications for any device used to correct the voltage regulation on a SWER network. With conventional storage systems the demand curve is predictable on a daily cycle, for example, large scale pumped hydroelectric storage schemes can be scheduled to generate for the 5:00PM to 7:00PM peak every day when consumption is known to be high. This scheduling would be unsuitable for a SWER line given the unpredictability of peaks and scheduling algorithms based on the network voltage or the measured demand are more suitable.

### **3.2.7.4. Line Impedance**

SWER networks are of a lower capacity than conventional feeders. They are also generally much longer, with a lower load density. This gives the lines unique electrical characteristics, they have a near unity leading power factor resulting from a high resistance to reactance ratio. The highly resistive long lines and smaller loads mean that the injection and consumption of active power on the network will yield larger and more predictable voltage improvements.

This has implications for any system employed to improve network voltage regulation. Injecting reactive power into the network will initially improve the voltage, but there will reach a point when no further improvement will be possible.

### **3.2.8. Existing Solutions to Improving SWER Line Voltage Regulation**

Poor voltage regulation on SWER networks is often caused by increased load. This can be as a result of new customers connecting to the network or increased consumption from existing customers. This is not a new issue and there are numerous methods commonly employed to address the problem.

### **3.2.8.1. Network Reconfiguration**

This is often a very expensive approach which should only be undertaken after serious consideration of alternative solutions. It is more suitable for areas where the load forecast shows continued growth. Often, only a portion of the SWER line will need to be converted, providing relief to the rest of the line. There are two possibilities:

- Augment the SWER network to duplex or triplex SWER
- Augment the SWER network to a conventional three phase feeder.

### **3.2.8.2. Augmentation of the Constrained Component**

Often, SWER network voltage regulation issues are a result of a single component causing a constraint in the network. Replacing a component could require minor works such as replacing a SWER isolation transformer, or major works such as replacing the conductor for the entire length of line.

### **3.2.8.3. Installation of Voltage Regulators**

Voltage regulators are a cost effective means of reducing voltage fluctuations to customers supplied from SWER networks. High Voltage regulators can be installed both on the SWER lines and upstream networks.

Low voltage regulators can be installed on an individual customer's supply. Low voltage regulators are connected to the LV terminals of the SWER distribution transformer and are most suitable for cases where there are only a small number of customers experiencing voltage fluctuations.

However, there are limits to the amount of augmentation that can be safely achieved with use of voltage regulators. The number of regulators that can be used varies depending on the feeder configuration. Before a new regulator is installed, network modelling of the following load rejection test must be completed:



- 1) Create a model of the existing network using network modelling software
- 2) Insert the new regulator into the model
- 3) Simulate the network at full load, regulator taps will usually be near their maximum
- 4) Simulate a fault causing a protection device to isolate a section of line
- 5) Monitor the network voltages given that the tap changer on the voltage regulators will take some time to adjust. If the network voltages do not exceed the levels described in Section 3.2.7.1, it is safe to install the new regulator onto the network
- 6) Repeat Step 3 and Step 4 for each protection device in the network.

#### **3.2.8.4. Installation of a Grid Utility Support Systems (GUSS)**

The Grid Utility Support System (GUSS) uses a battery bank and inverter to store energy from the network during periods of low demand and high network voltage and supply energy to the network during periods of high demand and low network voltage. The inverter is connected to the network via a SWER distribution transformer.

There are many manufacturers of Battery Powered Grid Utility Support Systems. Ergon Energy currently has a number of Magellan Power GPSS – SWR systems installed throughout its SWER network. These units are able to store 100 kWh of energy in their Lithium Phosphate ( $\text{LiFePO}_4$ ) batteries. They utilise a 25 kVA IGBT based bidirectional inverter which is able to operate in all four quadrants. They are a self-sufficient unit that come in a shipping container style enclosure.

The units have been successful in improving the voltage regulation on SWER networks and reducing capital expenditure by deferring major upgrades of the network. As stated previously, SWER lines typically have high resistance and a power factor which is close to unity, there is therefore limited voltage improvement to be made by exporting reactive power.

For the reasons detailed in Section 3.2.7.3, the scheduling algorithm employed by Ergon Energy uses network voltage to control the GUSS units. Because battery storage is limited and expensive, when a low voltage occurs on the network, the GUSS unit exhausts any improvement that can be made by exporting reactive power before exporting any of its valuable active power.

The units have many advantages including their low cost, portability and ease of installation. The power electronics based inverter is also very responsive to voltage fluctuations, much faster than the tap changer on a voltage regulator. The main disadvantage of this solution is the limited life of its batteries.

Figure 4 shows the connection diagram of a typical GUSS connected to a SWER feeder. This diagram highlights another advantage of a GUSS which is the ability to continue to supply a customer from its LV supply in the event of a network outage.

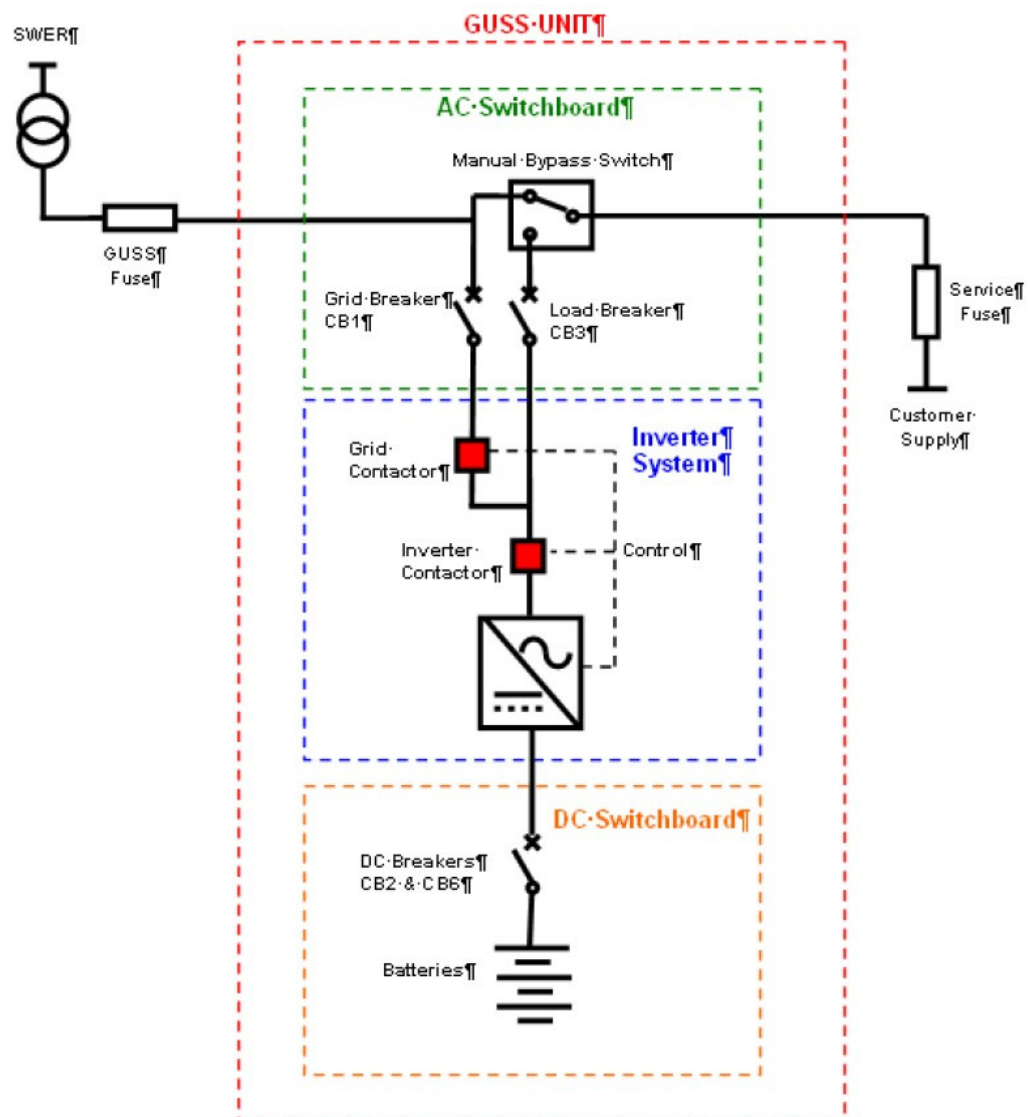


Figure 11 - Connection Diagram of a Typical GUSS (Louis, 2013)

### 3.2.8.5. Installation of Static Synchronous Compensator (STATCOM)

A STATCOM is a power electronics device that improves power factor by importing reactive power from the network or exporting reactive power to the network. As they do not have the ability to import or export active power, and because SWER networks often operate at near unity power factor, their effect on network voltage regulation can be limited.

### **3.2.8.6. Installation of Switched Reactors**

A switched reactor is a device that improves the network power factor by switching in reactor banks at predetermined voltage thresholds. As SWER networks can operate at a slightly leading power factor, they can provide some network voltage improvement. However, they do not have the ability to import or export active power, as detailed in Section 3.2.7.4, this limits their effect on network voltage regulation.

### **3.2.8.7. Installation of Embedded Fossil Fuel Powered Generation**

Embedded diesel or other fossil fuel powered generation can be used to improve voltage regulation of the network. However, the high operating and maintenance costs of this technology make it more suitable for applications where the network constraint only occurs occasionally, for example, a summer peak during extreme weather conditions occurring daily for one week per year.

### **3.2.8.8. Implementation of a Demand Management Solution**

There are a range of demand management solutions that can be implemented to improve network voltage regulation. These include:

- Using off peak tariffs to control appliances such as hot water heaters.
- Changing appliances to other energy sources, for example changing electric stoves to gas.
- Making electric appliances more energy efficient, for example installing fluorescent light bulbs.
- Making businesses and households more energy efficient, for example installing insulation in ceilings.

These solutions can help to defer network capital investment when the appropriate incentives are offered to encourage customers to adopt them. However there are limits to the reduction in peak load that can be achieved with this method.

## **4. Design a Pumped Hydroelectric Storage Plant**

### **4.1. Electrical Design Options Analysis**

There are a number of options available for achieving the electrical design requirement of this project as detailed in this Section.

#### **4.1.1. Conventional Synchronous Generator**

Large hydroelectric generators are synchronous alternating current machines. They also act as a motor in a pumped hydroelectric storage system when it is in pumping mode. They operate at a lower voltage such as 11 kV and connect to the transmission network via a step up transformer.

Conventional synchronous generators have rotor windings that are excited via brushes by a DC generator called an exciter. They have the ability to operate in all four quadrants:

##### Reactive Power Control

An over-excited machine will export reactive power onto the network whereas an under-excited machine will import reactive power from the network. Reactive power can be controlled in this manner regardless of whether the plant is in power generation mode or pumping mode.

##### Active Power Control:

Active power is controlled by the governor which actuates a valve to vary the flow of water supplied to the turbine. Increasing the flow of water to the turbine increases its torque output. In generation mode, increasing the torque applied to the generator increases the active power exported to the network. When the generator is operating as a motor, the machine will import active power from the network.

#### **4.1.2. Brushless Synchronous Generator**

Brushless synchronous generators operate in a similar fashion to conventional synchronous generators and can be connected directly to the network or via a rectifier and inverter. They can also be used as a stand-alone supply. They have two main components:

### The Exciter

This has a stationary field winding and a rotating armature winding. Its output is rectified to produce the field for the main generator.

### The Main Generator

This has a rotating field winding and a stationary armature winding. Its output can be rectified to produce the main DC output.

The units have a high level of reliability and reduced maintenance because they do not have brushes. They are generally configured to rotate at constant speed and have an Automatic Voltage Regulator (AVR) controlling the output by varying the exciter field current. Figure 12 shows the configuration of the Brushless Generator.

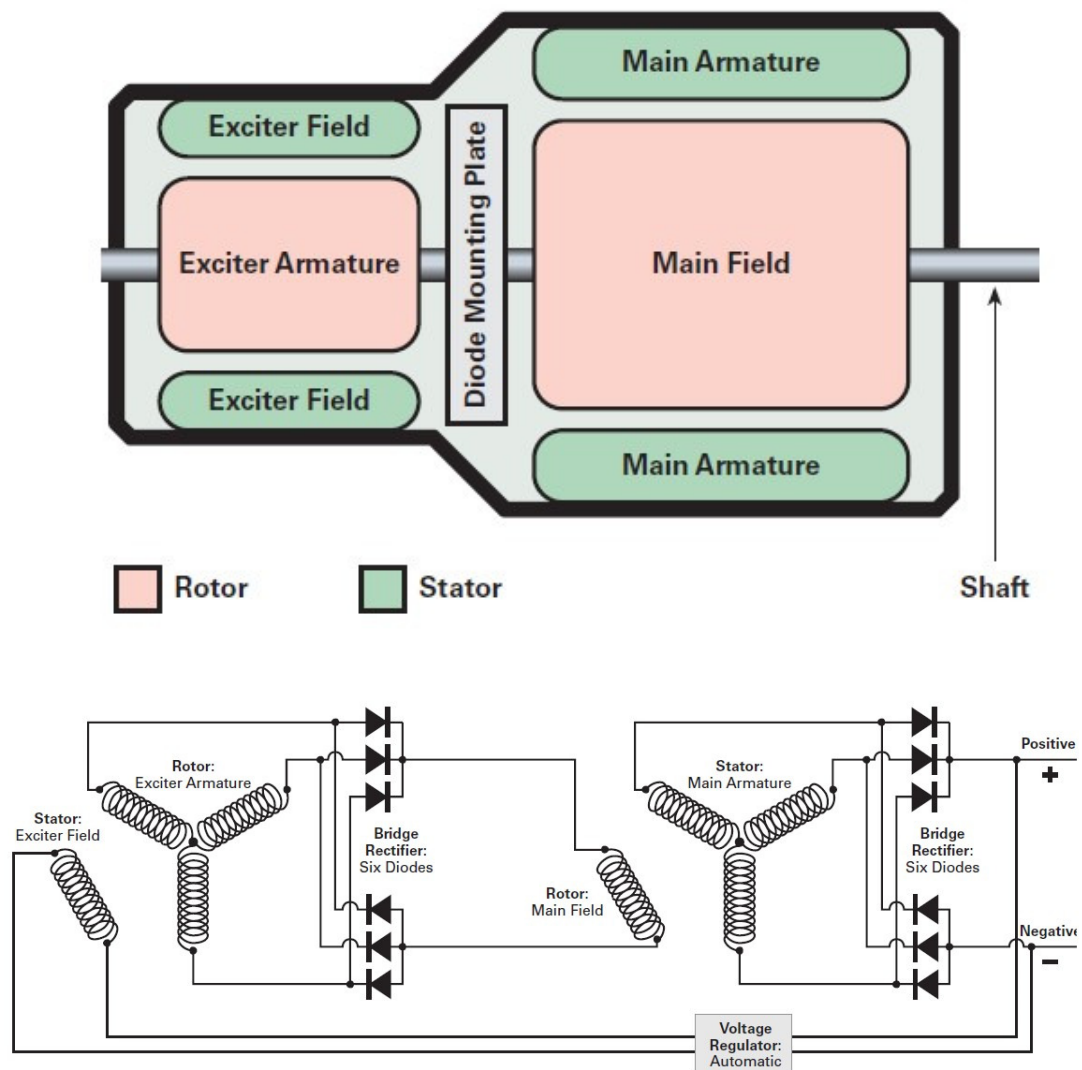


Figure 12 - Brushless DC Generator Configuration (Pearen, 2003)

#### **4.1.3. Asynchronous Generator**

Asynchronous generators are commonly used in small hydroelectric systems and varying sizes of wind turbine generators. An asynchronous generator can be constructed by simply rotating the rotor of a squirrel cage motor faster than its synchronous speed. This creates 'slip' which induces a current in the rotor bars creating the rotating magnetic field required to generate electricity.

Asynchronous generators must have an AC field present on their stator to begin generating electricity, they therefore can't be used to supply a dead buss. They can be connected to the grid directly or via an inverter system.

#### **4.1.4. DC Generator**

DC Generators are commonly used on small hydroelectric systems. They can be connected to an inverter directly or via a battery bank. Their main disadvantage is the fact that they contain brushes which increases their maintenance requirements and reduces their reliability.

#### **4.1.5. Permanent Magnet AC Generator**

A permanent magnet AC generator works in a similar fashion to a conventional synchronous generator however their rotor magnetic field cannot be varied and therefore their reactive power output cannot be controlled. Their main advantage is their simplistic design and control.

They are commonly used for small wind and hydroelectric generation application however this lack of voltage control makes them unsuitable for some applications.

## 4.2. Electrical Design Overview

A brushless synchronous generator – rectifier – inverter design was chosen for this project. Figure 13 illustrates the proposed electrical design of the pumped hydroelectric storage system.

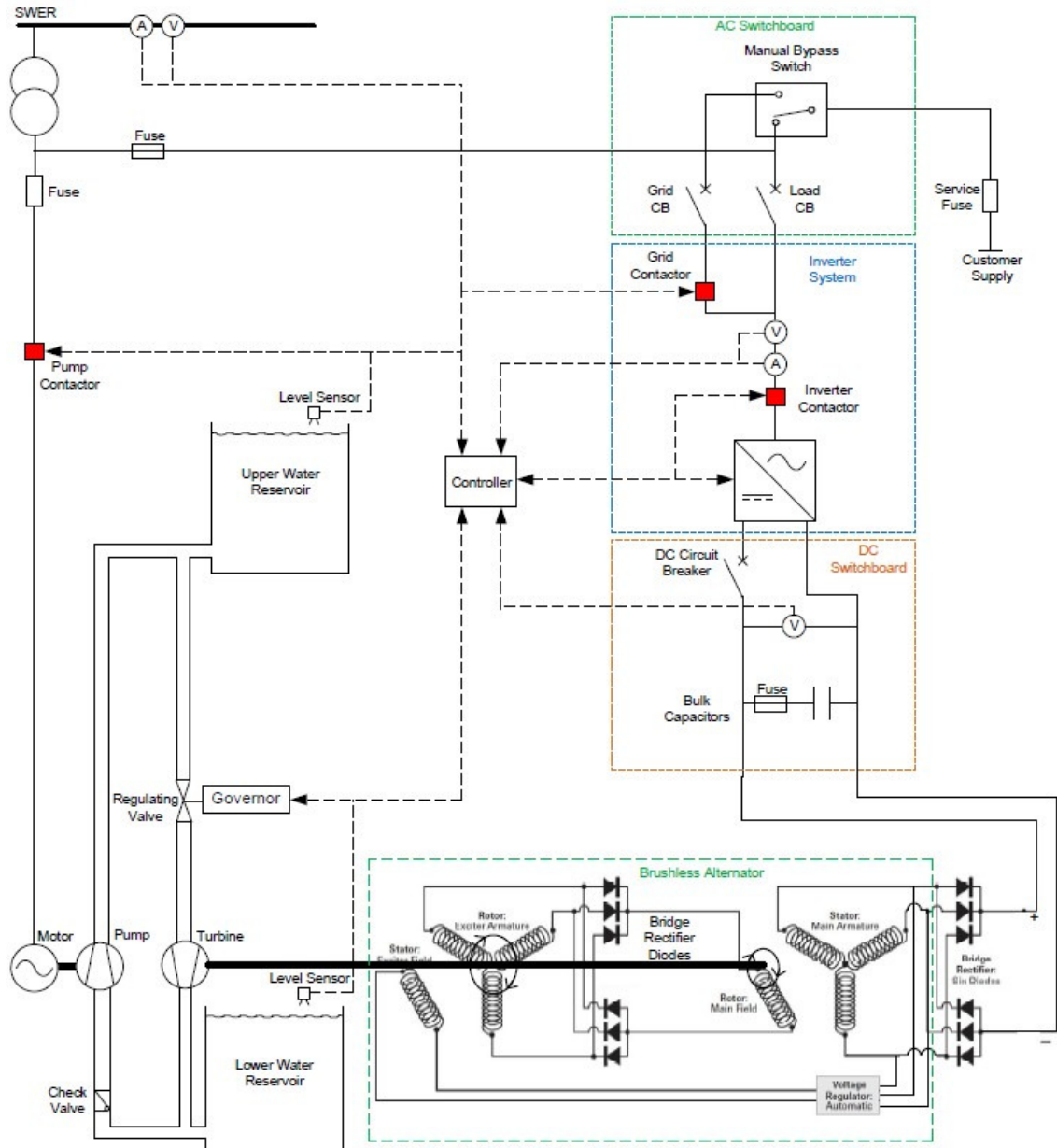


Figure 13 - Pumped Hydroelectric Storage System Electrical Design

This design was chosen for two reasons:

- 1) The brushless generator is more reliable and requires less maintenance than utilising a generator with brushes.
- 2) As opposed to the conventional synchronous generator design which needs to be spinning to control reactive power injection into the network, the inverter design can operate in this mode without consuming precious water resources.

#### **4.2.1. Modes of Operation**

##### STATCOM Mode:

In this mode the inverter imports reactive power from the network or exports reactive power to the network. This requires only control power for the inverter and can be done without the hydroelectric generator running. This is the preferred method of voltage control as it does not require the use of the real power stored in the hydroelectric system.

##### Pumping Mode:

The hydroelectric generator will be turned off and the pump contactor will be closed in order to recharge the upper storage reservoir. This would occur during periods of low power demand and higher system voltages.

##### Generating Mode:

In this mode the generator is operating and providing real power to the inverter. The inverter will operate in one of three quadrants as it exports real power to the network. This would occur during periods of high power demand and low system voltages.

#### **4.2.2. Features**

The system design which is illustrated in Figure 13 has the following features:

- An inverter that is able to perform voltage correction on the network by importing and exporting VARs without using real power from the generator. If a synchronous generator version were used instead of the GUSS inverter, VAR control would require the turbine to be spinning wasting the water resource.



- A brushless synchronous generator – rectifier – inverter design. The fact that this system does not need brushes reduces its maintenance requirements and improves the reliability of the system. The disadvantage of using this option is that the AC to DC to AC conversion introduces a small efficiency loss. Modern inverters have an efficiency of approximately 95%.
- The pumped hydroelectric storage system uses the water as the main storage medium. When this water storage is full, it is guaranteed to be able to deliver its full design capacity with no degradation over time. It also requires very little maintenance.
- The power electronics of the inverter is able to respond faster than other methods of improving voltage regulation. For example, this technology could be inserted into the network where a voltage regulator would fail the load rejection test (see Section 3.2.8.3. for details).
- The system utilises the inverter from the GUSS units currently used by Ergon Energy. Utilising this proven technology will therefore reduce the time and cost of a network trial.
- The system will be fully automated and will therefore require very little human intervention once setup.
- Some installations will have a seasonal rainfall inflow to the upper reservoir allowing low cost, environmentally friendly energy to be injected into the network. This will provide additional financial benefits for the owner.
- All components used in the proposed system are scalable to suit a particular network application.
- The system allows other renewables to be connected to the inverter such as wind and solar. This will reduce the net power consumption of the system however these must be carefully controlled to ensure that they exacerbate the voltage regulation problem.
- The proposed system design negates the need for some of the components used in direct grid connected synchronous generators. This is because it does not require a synchronising system and a variable set point controlled AVR and governor system.

### 4.2.3. Generator Design & Specifications

As shown in Figure 13, a brushless generator will produce an AC waveform which will be rectified to DC before supplying the system inverter.

The brushless generator chosen for this project is manufactured by Emerson. Appendix B shows the datasheet for the 4 Pole version though special order units with up to 24 poles are available from this manufacturer. This manufacturer provides a high quality product which can be purchased with an AVR module. They offer a number of AVR variations but the basic shunt type R220 was chosen because it is the lowest cost, highest reliability option.

The turbine speed determination is shown in Section 4.3.7.2. The number of poles the machine requires can therefore be calculated:

$$\text{Frequency} = 50 \text{ Hz} \quad \text{Speed} = 1000 \text{ RPM}$$

$$\text{Speed} = \frac{120 \times \text{frequency}}{\text{Number of Poles}}$$

$$P = \frac{120 \times \text{frequency}}{\text{Speed}} = \frac{120 \times 50}{1000} = 6 \text{ Poles}$$

The model chosen is the 28 kW, Leroy Somer, LSA 42.3 S4 6 Pole Brushless Generator. When connected in delta, its three phase output has a line voltage of 240 Volts RMS. This has been sized 3KW larger than the rated system output to allow for inverter efficiency losses.

### 4.2.4. Rectifier Design & Specifications

At 95% efficiency, the current drawn by the inverter at full load is:

$$I = \frac{P}{V \times 0.95} = \frac{25 \text{ kVA}}{297 \times 0.95} = 88.6 \text{ Amps}$$

The Semikron SKD 160 Bridge rectifier shown in Appendix C which is rated at 205 amps was chosen for this application. The high current rating was chosen to allow for elevated operating temperatures and a Semikron P3 150 heat-sink is sufficient for the cooling of the rectifier.

With the Delta connected generator providing a 240V RMS line voltage to the rectifier's input, the following calculations can be made.

The peak value of the rectifier output without smoothing:

$$V_P = \sqrt{2}V_{rms} = \sqrt{2} \times 220 = 339 \text{ Volts}$$

The minimum value of the rectifier output (ripple) without smoothing can occurs  $60^\circ$  from the zero crossing of the sine wave:

$$V_T = V_P \sin 60^\circ = 339 \times \sin 60^\circ = 294 \text{ Volts}$$

The mean value of the bridge rectifier output voltage without smoothing:

$$V = \frac{3\sqrt{2} V_L}{\pi}$$

Where  $V_L$  is the RMS of the line voltage of the 3 phase supply.

$$\therefore V = \frac{3\sqrt{2} 240}{\pi} = 324 \text{ Volts DC}$$

The output wave of the rectifier without smoothing is shown in Figure 14.

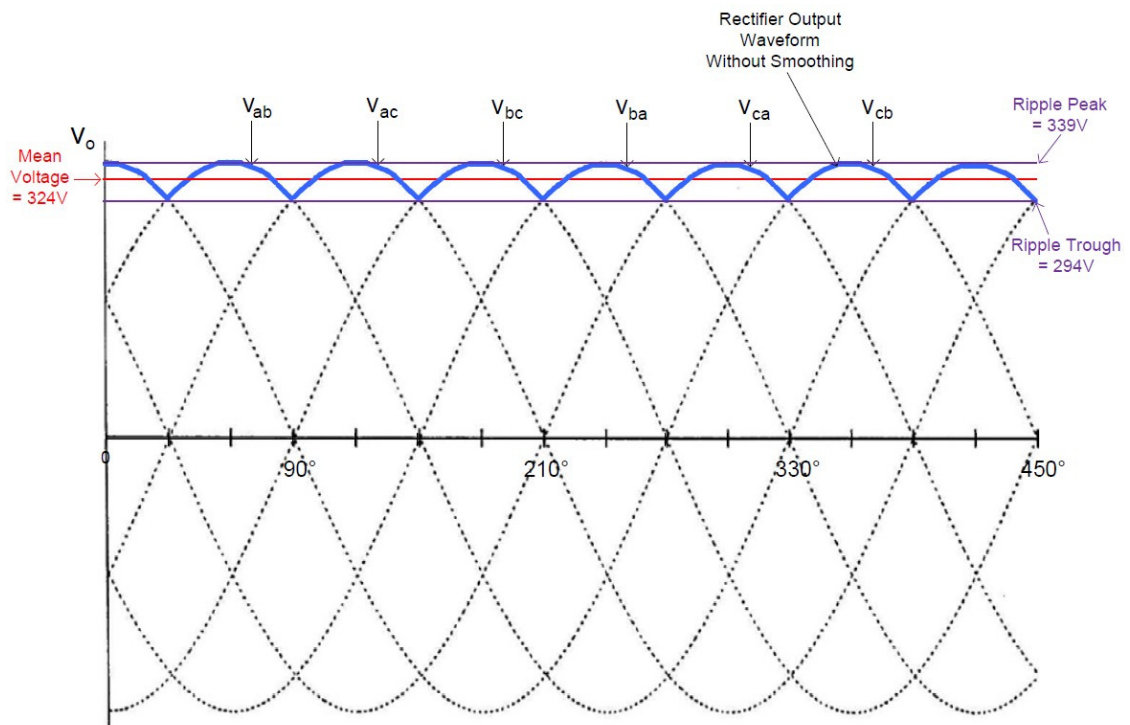


Figure 14 - Rectifier Output Waveform without Smoothing

#### 4.2.5. Capacitor Design & Specifications

The capacitor is aimed at reducing the pulsation of the rectifier output voltage which is known as ripple. Ripple can be substantially reduced with the addition of a smoothing capacitor but never eliminated. The size of the smoothing capacitor is therefore a compromise between cost and the smoothness of the DC voltage supplying the inverter. The life expectancy of the capacitor will also be greater with a larger capacitor and reduced ripple voltage.

Calculating the input impedance of the inverter at the worst case which is full load:

$$R = \frac{V}{I} = \frac{324 \text{ Volts}}{88.6 \text{ Amps}} = 3.7 \Omega$$

A practical rule for calculating the size of the filter capacitor required is as follows:

$$C = \frac{5 \times V_{max}}{\Delta V 2 f_p R_L} \quad (\text{Carpenter, Roden, \& Savant, 1987})$$

Where:

$V_{max}$  = Peak value of waveform with respect to the ripple minimum value

$V_{min}$  = Lowest acceptable waveform voltage with respect to ripple minimum value

$\Delta V = V_{max} - V_{min}$  = Peak to trough value of allowable ripple voltage = 2 Volts

$f_p$  = Frequency after full wave rectification

$R_L$  = Load Resistance

$$\therefore C = \frac{5 \times 42}{2 \times 2 \times 300 \times 3.7} = 47 \text{ mF}$$

Four EPCOS 15,000 $\mu$ F 400V capacitors were chosen to meet the requirements of this project. The details of this component are shown in Appendix D. The final waveform still has a peak value of 339 Volts though the trough voltage will be 337 Volts. This voltage is close to a pure DC and would appear as an almost straight line in the waveform shown in Figure 14.

The ripple at full load with the smoothing capacitor can be calculated as follows:

$$V_r = \frac{V_{max} - V_{min}}{2\sqrt{3}} = \frac{2}{2\sqrt{3}} = 0.58 \text{ Volts (rms)}$$

Note that the waveform now looks more like a sawtooth than a sine wave which is why the above formula includes  $\sqrt{3}$  in the denominator rather than  $\sqrt{2}$ .

#### **4.2.6. Inverter Design & Specifications**

There are many inverter products available on the market, however the Magellan four quadrant inverter was chosen for this project, see Appendix E for details. These are used in the GUSS units currently deployed in the Ergon Energy network. They have proven to be reliable and effective in solving network voltage constraints.

The inverters feature a range of communication protocols including Modbus RTU, Ethernet and Distributed Network Protocol 3 which will make interfacing the inverter easier. They are also easily connected to battery and solar systems should the need arise.

Modern Magellan inverters accept a DC voltage input ranging from 300 Volts to 410 Volts to suit Lithium-Ion battery banks. The above near DC voltage (339 Volts Peak with 0.58 Volts RMS ripple), has been designed to suit the requirements of the Magellan inverter.

#### **4.2.7. Controller Design & Specifications**

This system will be unattended and will thus require automatic control. Because of the small number of inputs and outputs that will be connected to the controller, a Programmable Logic Controller (PLCs) was chosen to perform this function. Benefits of PLCs include their low cost, flexibility and ease of programming. One PLC is sufficient to control all components of the system.

There are many manufacturers of PLC technology, for example, Siemens, ABB, Allen Bradley and Mitsubishi. The brand purchased will be the best priced system that provides the required functionality.

#### 4.2.8. Generator Speed & Frequency Control

Figure 15 shows the block diagram of the generator speed and frequency control.

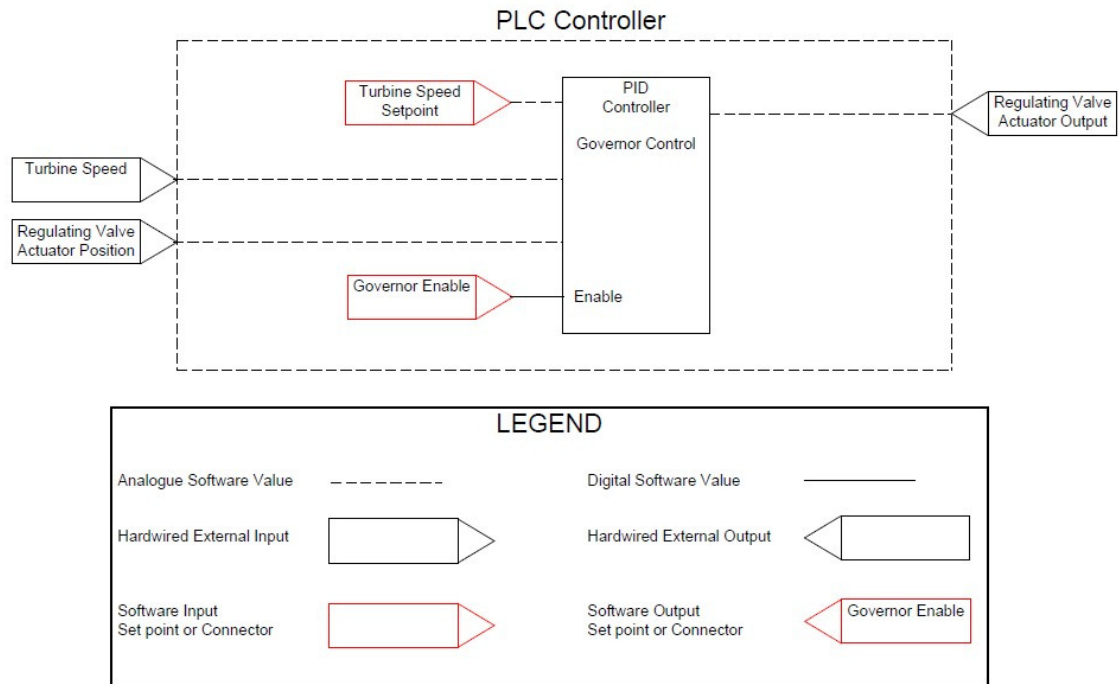


Figure 15 – Generator Speed and Frequency Control Block Diagram

The turbine and generator have been selected to operate at 1000 RPM which produces a generator output at 50Hz. The function of the generator speed and frequency control loop is to maintain this constant set point when active power injection is required.

The governor consists of a PID control loop within the PLC. When the PLC determines that active power is required, it enables the control loop. The PID loop then uses the turbine speed and actuator position sensors to determine the water regulating valve's set point. This in turn controls the water flow to the turbine and regulates the turbine speed.

#### 4.2.9. Generator Voltage Control

It is proposed to purchase a Leroy Sumer Brushless Generator with a shunt type R220 AVR controller. Shunt type AVR's source their power from the output of the generator which is a more simplistic and reliable design when compared to other types of AVR's that source their power from an alternative supply. As shown in Figure 16, this type of AVR has a very compact design. The AVR regulates the delta connected generator output line voltage to 240 Volts AC (RMS). Figure 17 diagrammatically represents the control function that will be performed by the AVR.

## AVRs for SHUNT excitation



Type of AVR		LSA alternator type range									
		40	42.3	44.3	46.2	47.2	49.1	50.2	51.2	53.1	54
R220		.	.								
R250				.	.	.					
R450			option	option	option	option					
Module	R726		option	option	option	option					
	R731		option	option	option	option					
Digital	D510C	option*	option	option	option	option					

Figure 16 - Leroy Somer Shunt Type AVR Controller (Emerson, 2014)

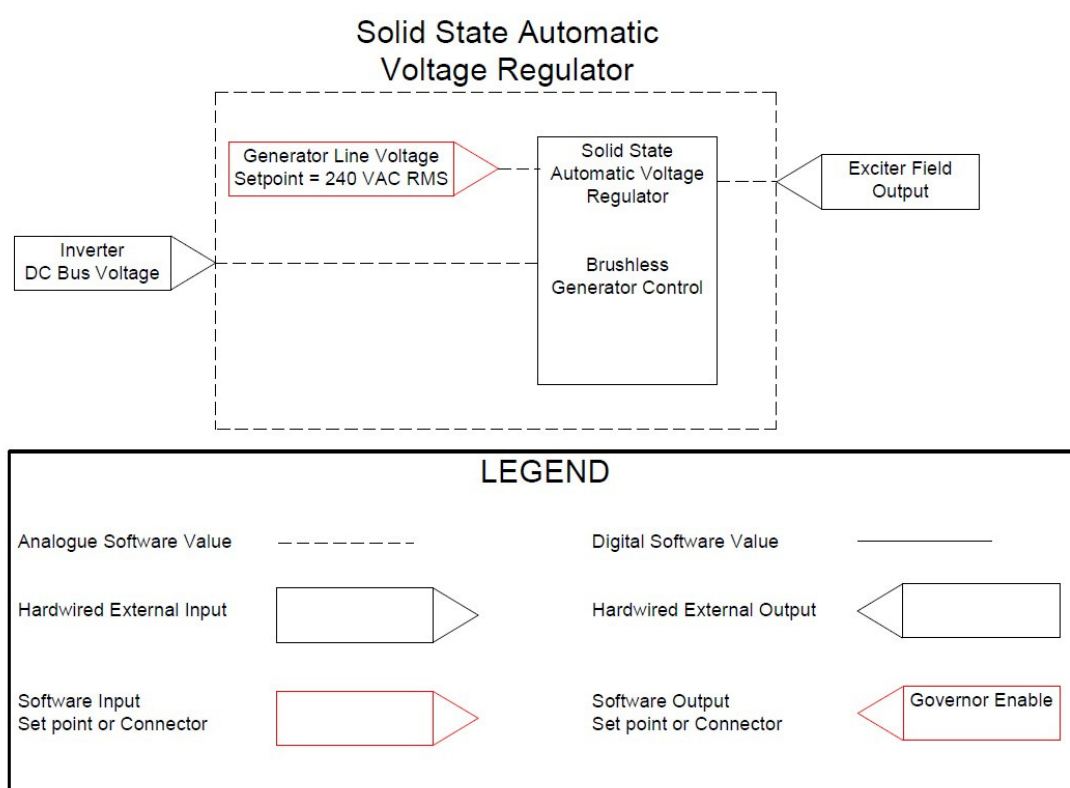


Figure 17 – Generator Voltage Control Block Diagram

### 4.2.10. Inverter Power Control

Inverter power will be controlled by two P&ID loops programmed within the PLC. The first loop will control reactive power based on network voltage. If the voltage of the network falls below the desired range, the PLC will increase the reactive power (VAR) setpoint until unity power factor is reached. The system will be operating in STATCOM mode.

A point will be reached when all reactive power options for improving the network voltage have been exhausted and one of the two conditions will occur:

- The network will reach unity power factor
- The inverter will reach its reactive power limit

At this point, the PLC will start the hydro-electric generator and inject active power into the network until the desired network voltage is reached. Figure 18 diagrammatically represents the power control loop described.

It is proposed to operate the power control loop in this manner in order to conserve the precious water resource which will only be depleted when active power is being injected into the network.

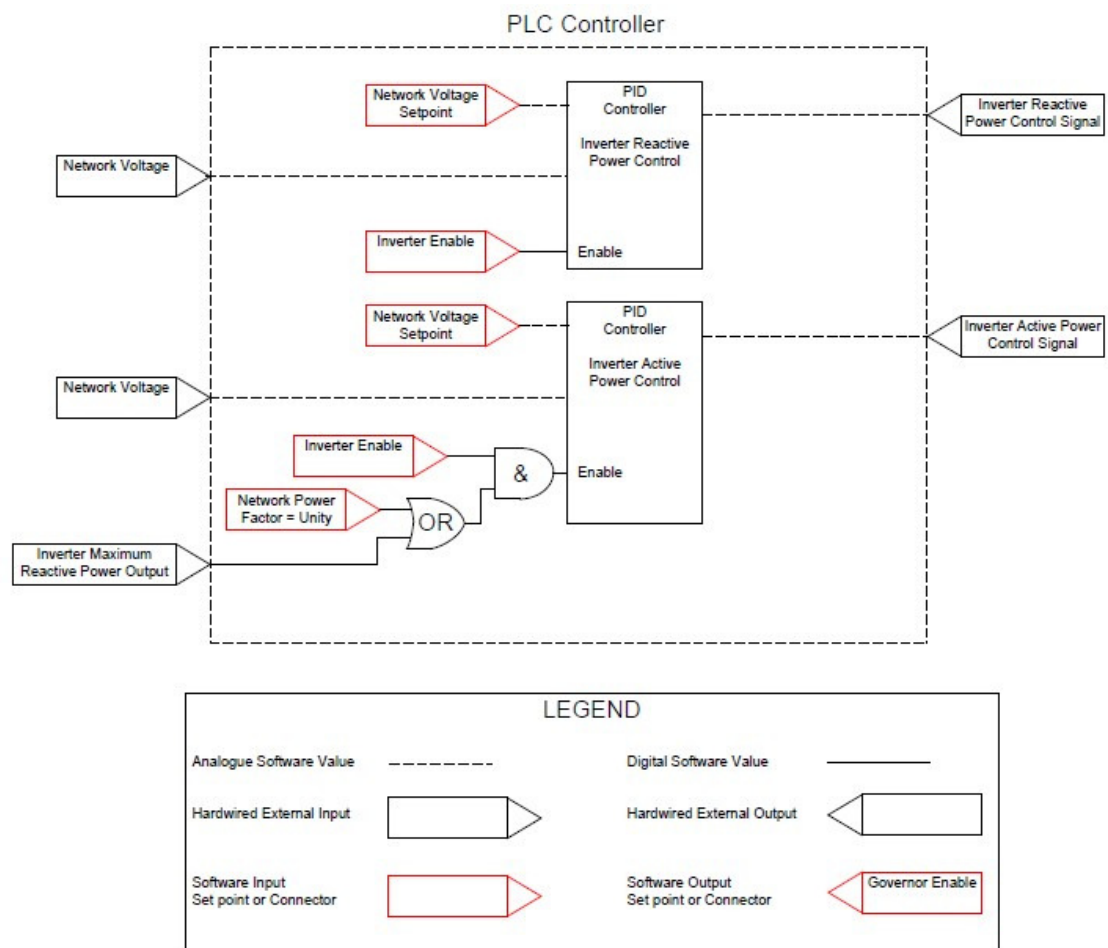


Figure 18 - Inverter Power Control Block Diagram



#### 4.2.11. System Controls

The PLC will be the central controller for the system and will monitor and control a wide range of inputs and outputs, such as DC battery voltage, reservoir levels, the pump contactor, etc. It is expected that the PLC will send an alarm to the control room when any of these conditions become abnormal. Figure 19 shows some of these signals.

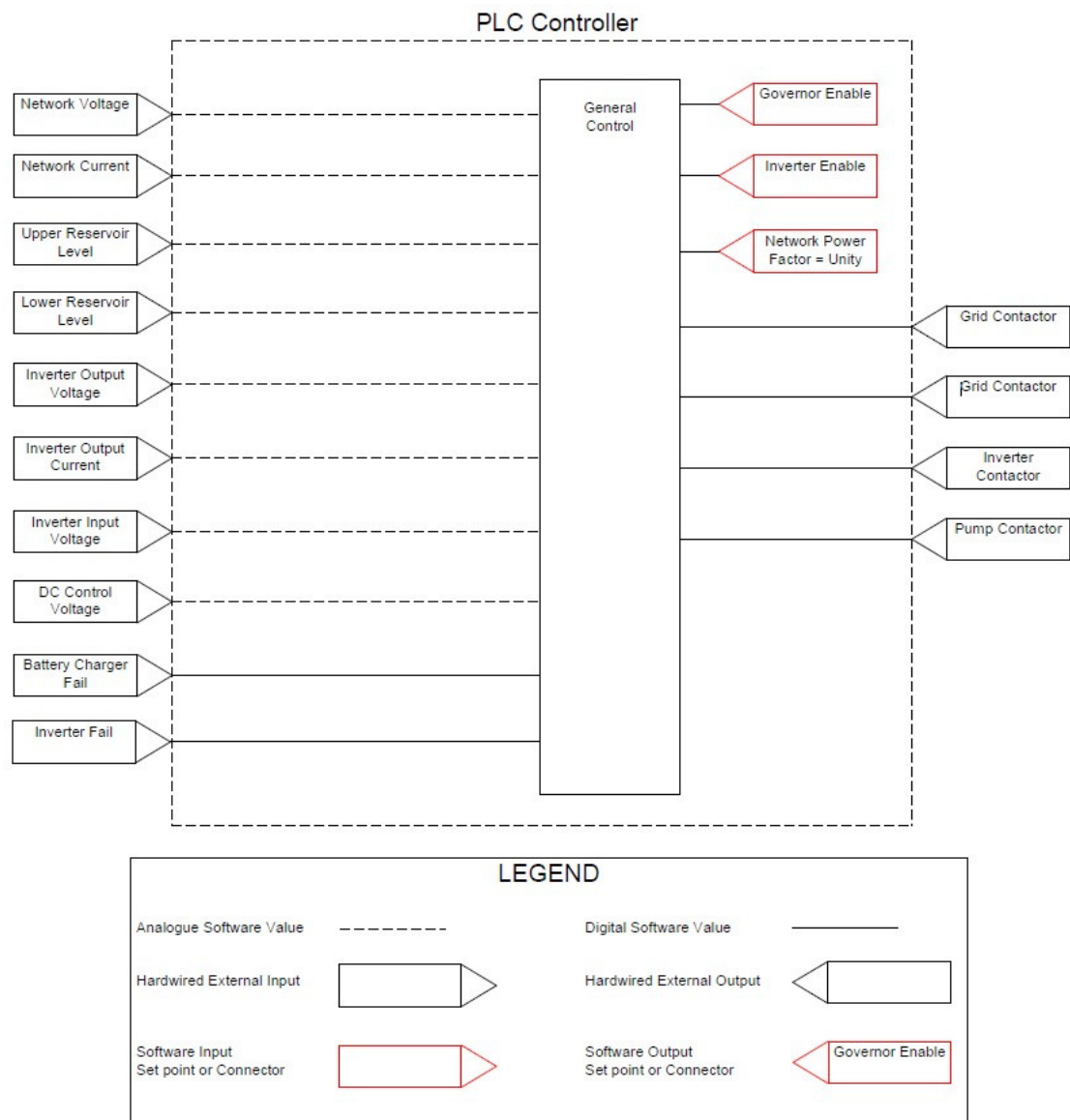


Figure 19 - Pumped Hydroelectric Storage System Control Block Diagram

#### **4.2.12. Network Undervoltage Response Sequence**

The following sequence of events is an example of how the controls described in previous sections will combine in response to a network undervoltage condition:

- 1) The PLC controller senses that the network voltage has reduced to beyond a predetermined threshold.
- 2) The PLC controller increases the reactive power setpoint to the inverter.
- 3) The inverter operates in STATCOM mode, injecting reactive power into the network. The hydroelectric generator is not operating at this stage as the inverter only requires a small amount of power from the DC control voltage supply to operate in this mode.
- 4) The PLC senses that unity power factor has been reached.
- 5) The PLC enables its governor control loop which regulates the generator speed at 1000 RPM.
- 6) The generator's AVR automatically regulates the generator line voltage to value of 240 Volts AC (RMS).
- 7) The PLC Increases the active power setpoint to the inverter.
- 8) Due to the increased current drawn by the inverter, the voltage to inverter input reduces.
- 9) The AVR & generator respond by increasing their output.
- 10) As the generator's output has increased, the torque exerted on the turbine will increase causing its speed to droop.
- 11) The PLC will sense the reduced turbine speed, and open the regulating valve until a turbine speed of 1000 RPM is reached.

### **4.3. Mechanical Design**

#### **4.3.1. Design Parameters**

Ergon Energy's SWER feeders are all located in low density, rural and often remote areas. This makes them ideal for the construction of pumped hydroelectric storage technology. However, the nature of the high and low level dam will vary greatly, depending on what is available near a particular SWER network. This design assumes the specifications detailed below:

System Rated Output:	25 kVA
Required Storage Capacity:	100 KWh
Dam Head Height at Full Capacity:	40 m
Dam Head Height When Empty:	38 m
Penstock Length:	150 m
Operating Time at Full Load:	4 Hours

These specifications describe a medium head micro hydroelectric scheme.

One of the objectives of this section is to assess the specifications that would be required for a hydroelectric equivalent of the GUSS systems currently used in the Ergon Energy network. In order to achieve this objective, similar electrical specifications were chosen.

#### **4.3.2. Dam or Weir**

This is the water storage device that is required to increase the head, to provide water storage and to smooth out daily and seasonal water flows as required. In a pumped hydroelectric storage scheme there are usually two of these structures, one forming the upper storage and the second forming the lower storage.

Dam and weir structures vary from small earthen structures found on rural properties to large concrete structures holding many years of water supply.

The energy that can be generated by a hydroelectric generator from a dam can be derived using the following formulas:

$$E = mgh \text{ (joules)}$$

$$m = V \times \rho$$

Combine these Formulas:

*Equation 2:*

$$E = V\rho gh \text{ (joules)}$$

Convert to kWh:

$$E = \frac{V\rho gh}{3600000} (kWh)$$

Multiplying by the efficiency factor of the hydroelectric system ( $\eta$ ):

$$E = \frac{\eta V\rho gh}{3600000} (kWh)$$

The head height will constantly vary, assume that the average of the high and low dam level:

$$E = \frac{\eta V\rho g \left[ H_1 - \frac{H_1 - H_2}{2} \right]}{3600000} (kWh)$$

Where:  $\eta$  = Hydroelectric System Efficiency = 70% (Typical for Micro Hydro-Electric Systems)

$\rho$  = Density of Water = 1000 kg/m<sup>3</sup>

$g$  = Acceleration Due to Gravity = 9.81 m/s<sup>2</sup>

$H_1$  = Head Height at Full Dam Capacity

$H_2$  = Head Height at Empty Dam Capacity

$V$  = Dam Volume at Full Capacity (m<sup>3</sup>)

$E$  = System Output Energy Storage Capacity (kWh)

Rearrange this formula to calculate the required dam volume:

$$V = \frac{7200000}{(H_1 - H_2)\eta\rho g} \times E \text{ (m}^3\text{)}$$

Substituting in the known system parameters:

$$\therefore V = \frac{3600000}{39 \times 0.7 \times 1000 \times 9.81} \times 100 \text{ (m}^3\text{)}$$

$$\therefore V = 1,344 \text{ m}^3$$

$$\therefore V = 1,344,000 \text{ Litres}$$

These calculations show that the dam requirement for a 100 kWh storage capacity and a low level head height of 38m is a volume of 1,344 m<sup>3</sup>. This can be achieved with a dam of the following dimensions: 25.9m Long x 25.9m Wide x 2m Deep. Figure 20 shows a diagrammatic representation of these requirements.

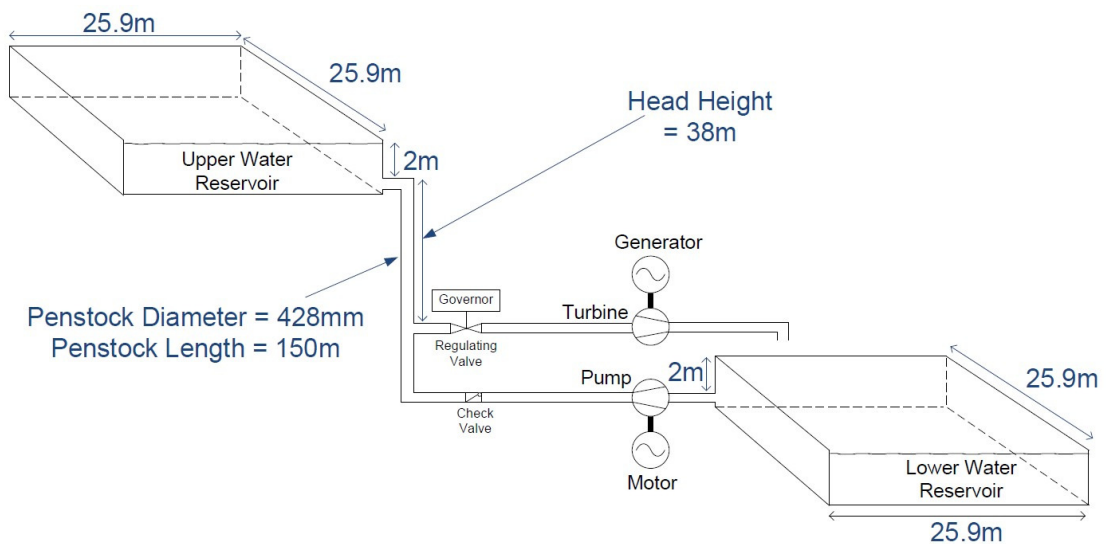


Figure 20 – 25 kVA, 100 kWh PHS Mechanical Design Requirements

This equates to 13,440 Litres (or 13.4 m<sup>3</sup>) per kWh at a 39 m head height. Therefore one kWh of energy could be stored with a dam elevated at 38m which is 2.6 m Long x 2.6 m Wide x 2m Deep.

#### 4.3.3. Instantaneous Flow

With a rated system real power output of 25 kW and a system efficiency of 70%, the system input energy can be calculated:

$$Efficiency = \frac{Output\ Power}{Input\ Power}$$

$$\therefore Input\ Power = \frac{Output\ Power}{Efficiency}$$

$$\therefore Input\ Power = \frac{25\ kW}{0.7} = 35.71\ kW$$

When the dam is at its average level, the head height will be 39m, the flow of water required to maintain this output power can be calculated:

Using Equation 2:

$$E = V\rho gh\ (joules)$$

Convert to Watts (Joules/Second):

$$\therefore Power = \frac{E}{t} = \frac{V\rho gh}{t}\ (Watts)\ \text{where } t = \text{time (seconds)}$$

$$\therefore P = Q\rho gh\ (Watts)\ \text{where } Q = \text{flow (m}^3/\text{sec)}$$

Rearrange:

$$Q = \frac{P}{\rho gh}$$

$$\therefore Q = \frac{35710}{1000 \times 9.81 \times 39}$$

$$\therefore Q = 0.0933\ m^3/sec = 93.3\ Litres/sec$$

Calculation Check:

$$93.3 \text{ Litres/sec} \times 60 \text{ Sec/min} \times 60 \text{ min/hour} \times 4 \text{ hours} \\ = 1,344,000 \text{ Litres Per } 100\text{kWh Output Discharge Cycle}$$

This agrees with previous calculations.

#### **4.3.4. Spillway**

This is the structure built to protect the dam or weir when large inflows occur. The spillway type chosen for this project is the overflow gravity type shown in Figure 21. It is the most common type of spillway used because of its simplistic design. Its smooth shape is designed to minimise pressure and therefore erosion on its surface and dissipate the energy from the falling water. The spillway construction material chosen for this project is concrete because of its erosion resistant properties.



*Figure 21 - Overflow Gravity Type Spillway (Penche, 1998)*

#### 4.3.5. Intake

The intake structure is the structure at the transition between the river or dam and the conduit supplying the power plant. The intake must be hydraulically and structurally sufficient for the volume of water. It must also remove debris and sediment from the water to ensure the turbine has a clean supply for optimum reliability and minimal wear.

There are many types of intakes, the left side of Figure 22 is an intake used in water reservoirs and the right side is a drop intake which is installed directly into stream-flow.

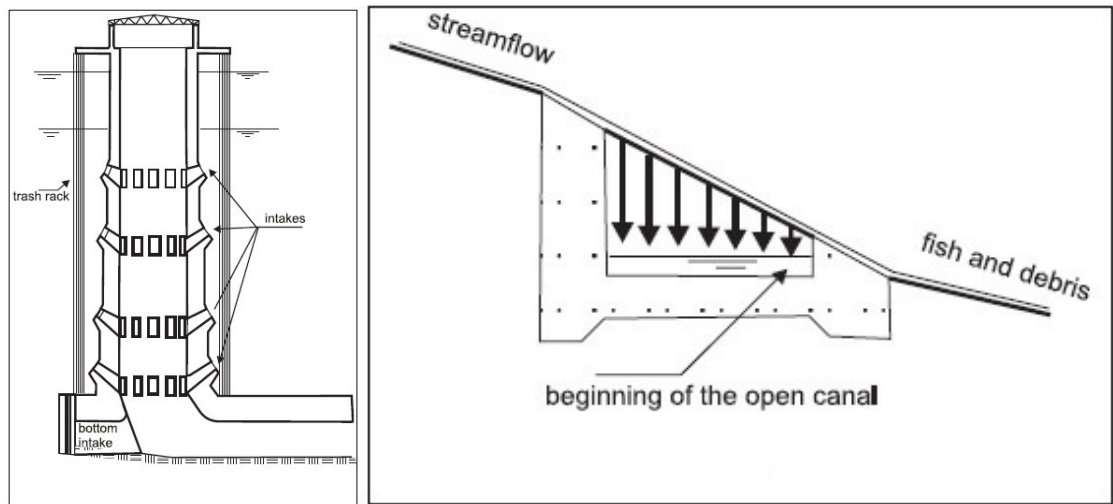


Figure 22 - Hydroelectric Plant Intake Structures (Penche, 1998)

The intake arrangement shown in Figure 23 was designed because of the small capacity, low cost and unattended plant design parameters of this project.

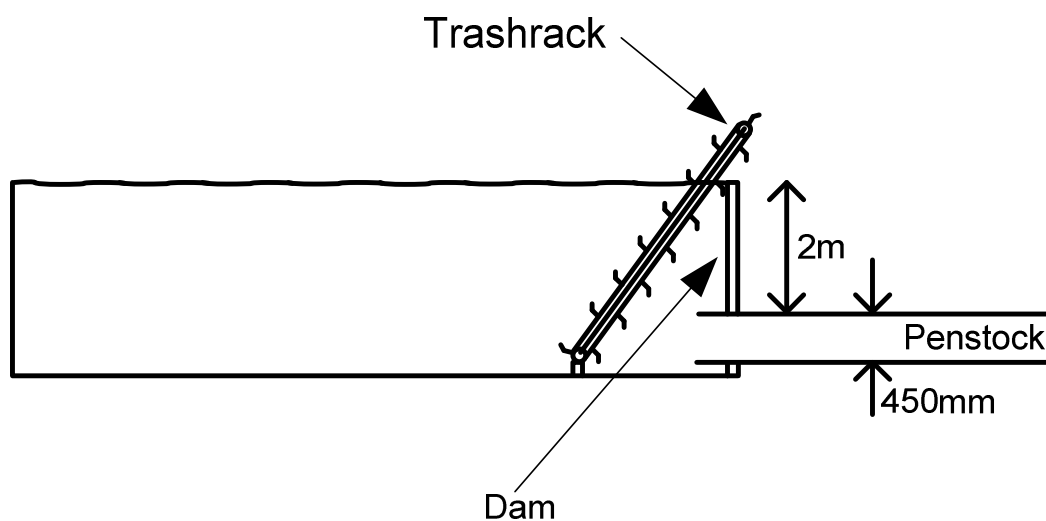


Figure 23 - Hydroelectric Plant Inlet Design



The trashrack is commonly used in hydroelectric plants and comprises of evenly spaced bars across the intake which capture debris sucked into the intake. An electric motor will drive chain linked fingers across the bars to remove the debris. The device will not operate continuously but on a timed basis. Usually, once per day for five minutes is sufficient but this will depend on how much debris are present.

#### 4.3.6. Penstock

This is the pipe that transfers the water from intake structure to the turbine. Penstocks can be aboveground or underground and can be constructed from a range of materials including steel, plastic, plain spun or pre-stressed concrete, glass re-enforced plastic (GRP) and PVC.

There are a wide range of joint types including welded, spigot and socket, sleeve and bolted flanges. This must be designed to suit the penstock material, pressure requirements and location of the hydroelectric plant.

Penstock diameter is a compromise between cost and power loss. The smaller the pipe diameter, the higher the water velocity within the pipe will be, resulting in higher friction and turbulence losses.

A common approach for calculating the penstock size is to specify the maximum permissible head loss of the system and calculate the pipe diameter using Equation 3 :

*Equation 3 (Penche, 1998):*

$$Diameter = 2.69 \left[ \frac{n^2 Q^2 L}{H} \right]^{0.1875}$$

*Where  $n$  = Percentage Power Loss*

*$Q$  = Turbine Discharge Flow ( $m^3/sec$ ),*

*$L$  = Penstock Length ( $m$ ),*

*$H$  = Gross Head ( $m$ ) = 38m which is the worst case scenario.*

For this project a 4% loss has been deemed acceptable, this is a common figure used for hydroelectric projects.

Using Equation 3:

$$\therefore \text{Diameter} = 2.69 \left[ \frac{0.04^2 0.0933^2 150}{38} \right]^{0.1875}$$
$$\therefore \text{Diameter} = 0.428\text{m} = 428\text{mm}$$

Therefore a penstock with an internal diameter of 450mm has been chosen for this project.

#### **4.3.7. Turbine**

The turbine converts the potential energy contained in the water head into mechanical rotational energy which rotates the generator.

##### **4.3.7.1. Turbine Classification**

###### Reaction Turbines

The turbine is completely immersed in water and rotates by reacting to the pressure applied to the face of the runner blades. The pressure drops as it passes through the turbine. The case of the reaction turbines must be strong enough to withstand the full head pressure of the hydroelectric scheme.

Examples of reaction turbines include the Francis and Kaplan Turbines

###### Impulse Turbines

Impulse turbines are characterised by a change in the direction of flow of a high velocity jet of water. They operate by directing a jet of water at the turbine blades. The pressure drop does not take place on the turbine blade (as it does in a reaction turbine), but it takes place in the nozzle. The casing of an impulse turbine does not need to be pressure rated as it does nothing more than prevent the splashing of water.

Examples of impulse turbines include the Pelton, Turgo and Cross-flow turbines.

#### 4.3.7.2. Turbine Selection

There are a number of manufactures that could be used for the supply of the turbine and associated equipment. For this project, Gilbert Gilkes & Gordon was chosen because of their extensive experience in the area. The company offers a Compact Hydro Turbine Range specifically for applications of less than 100 kW. The units come complete with isolation valves and flow regulating spear valves. Figure 26 shows an installed hydroelectric system from this series.

In accordance with the project specifications and the Gilkes charts shown in Figure 24 and Figure 25, the 1000 RPM 12 inch 30 kW Turgo turbine has been chosen.

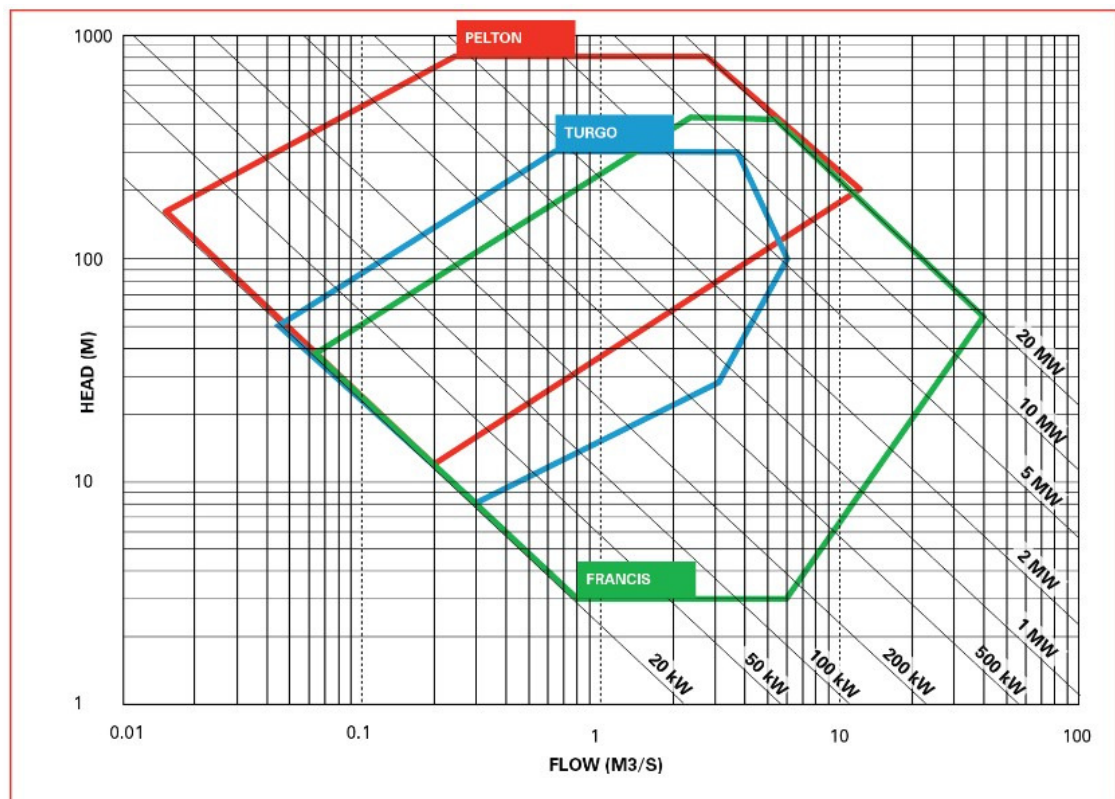


Figure 24 - Hydro Turbine Characteristics (Gilbert Gilkes & Gordon, 2014)

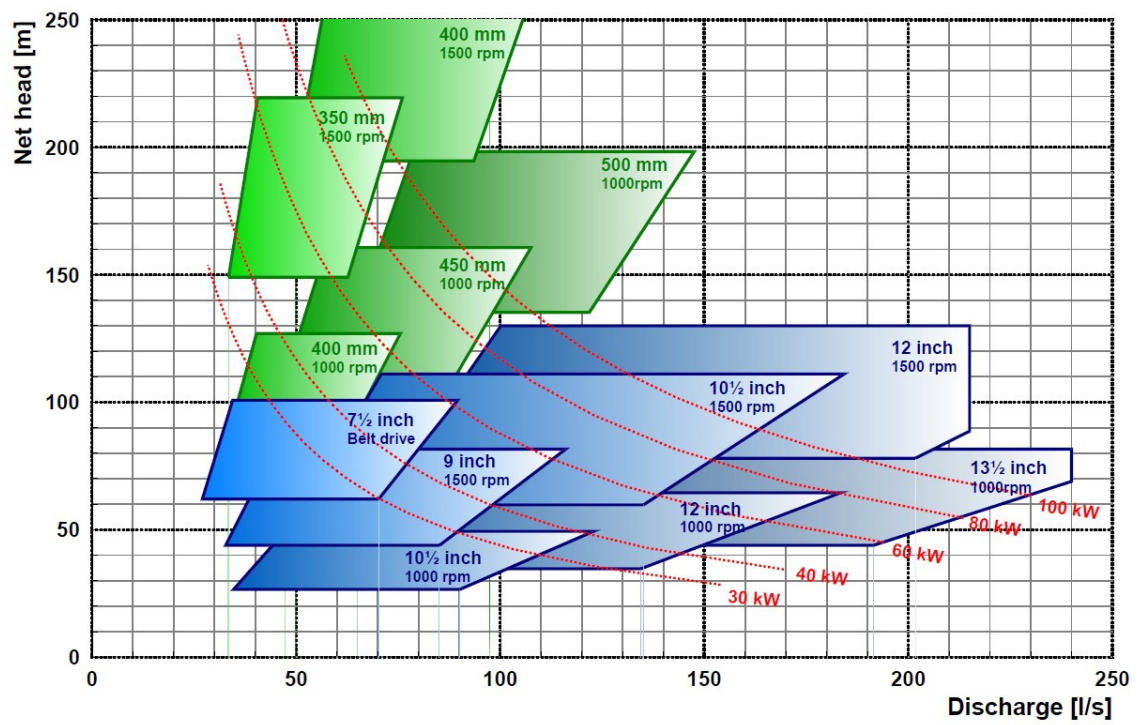


Figure 25 - Gilkes Compact Hydroelectric System Selection Chart (Gilbert Gilkes & Gordon, 2014)



Figure 26 - An Installed Gilkes Compact Hydroelectric System (Gilbert Gilkes & Gordon, 2014)

## 5. Model the effects of a Pumped Hydroelectric Storage Plant on an Ergon Energy SWER feeder.

### 5.1. Simulation Software Options

There are a range of simulation software options available:

#### DINNIS

DINNIS (Distribution Network Information System) is a Fujitsu product has been used by Ergon Energy since the 1980's. Ergon energy has developed a library of conductors and line configurations that it regularly uses to expedite the building of network models. However, the product is no longer supported by Fujitsu and has a number of disadvantages including the following:

- It has a limited and outdated component library. For example, modern technologies such as PV systems, wind turbines or power electronics devices are not included in the library.
- It is a three phase analysis tool with accuracy issues when modelling single phase devices.
- Bulk parameter changes are cumbersome as they are executed via macros importing the data from Microsoft Excel.
- It cannot show the network in a schematic format, only in a geographical layout.

#### MATLAB

MATLAB is a software package developed by the Mathworks Company. It is not a specialised network and load flow analysis program but code can be written to allow it to be used for this purpose. There are versions of this code already written by people within both USQ and Ergon Energy that could be adapted for this project.

The advantage of using MATLAB would be that it can be easily adapted to perform a dynamic network analyses with changing network conditions. However the disadvantages of using MATLAB for this application is because it is not a specialised network analysis software package, implementing and troubleshooting the code to simulate every node in a single SWER network would be time-consuming.

### PSS Sincal

PSS Sincal is a specialised Siemens network analysis software package used by Ergon Energy for applications where DINNIS is inaccurate or cumbersome such as single phase SWER networks and protection calculations. It has a Graphical User Interface (GUI) that displays the network in a GIS style layout. It is a user friendly and modern software package which can be easily customised to a particular application and allows bulk updates to be easily performed on the network model. This software package was chosen for the network analysis portion of this project.

## **5.2. The Wambo Creek SWER**

The Wambo Creek SWER which is located approximately 300km west northwest of Brisbane was chosen to model the pumped hydroelectric storage system, a schematic diagram representing the feeder as of May 2013 is shown in Appendix G. The 200 kVA 33/12.7 kV Joseph Road SWER Isolation transformer supplies the Wambo Creek SWER feeder. This SWER isolation transformer is supplied from the Chinchilla Substation Brigalow 33 kV Feeder.

Steady load growth has been experienced on the feeder and at the time of analysis, the peak load experienced on the system to date was 280 kVA. This is greatly in excess of the rating of the 200 kVA transformer that supplies it with urgent works required to rectify this problem and the poor voltage regulation of the network.

All Per Unit (pu) values used during this analysis assume a 200kVA, 19.1kV Base.

### 5.3. The Wambo Creek SWER Network PSS Sincal Model

The Wambo Creek SWER network PSS Sincal model consists of 159 nodes representing the entire high voltage network from the SWER isolation transformer to the customer's low voltage supply transformers. The model contains detailed data such as line lengths, conductor sizes and transformer impedances. The PSS Sincal tap changer used automatically changes tap depending on the network voltage during the analysis. Appendix H to Appendix L show the diagrammatic representations of the model and Figure 27 shows the symbols used by the model.

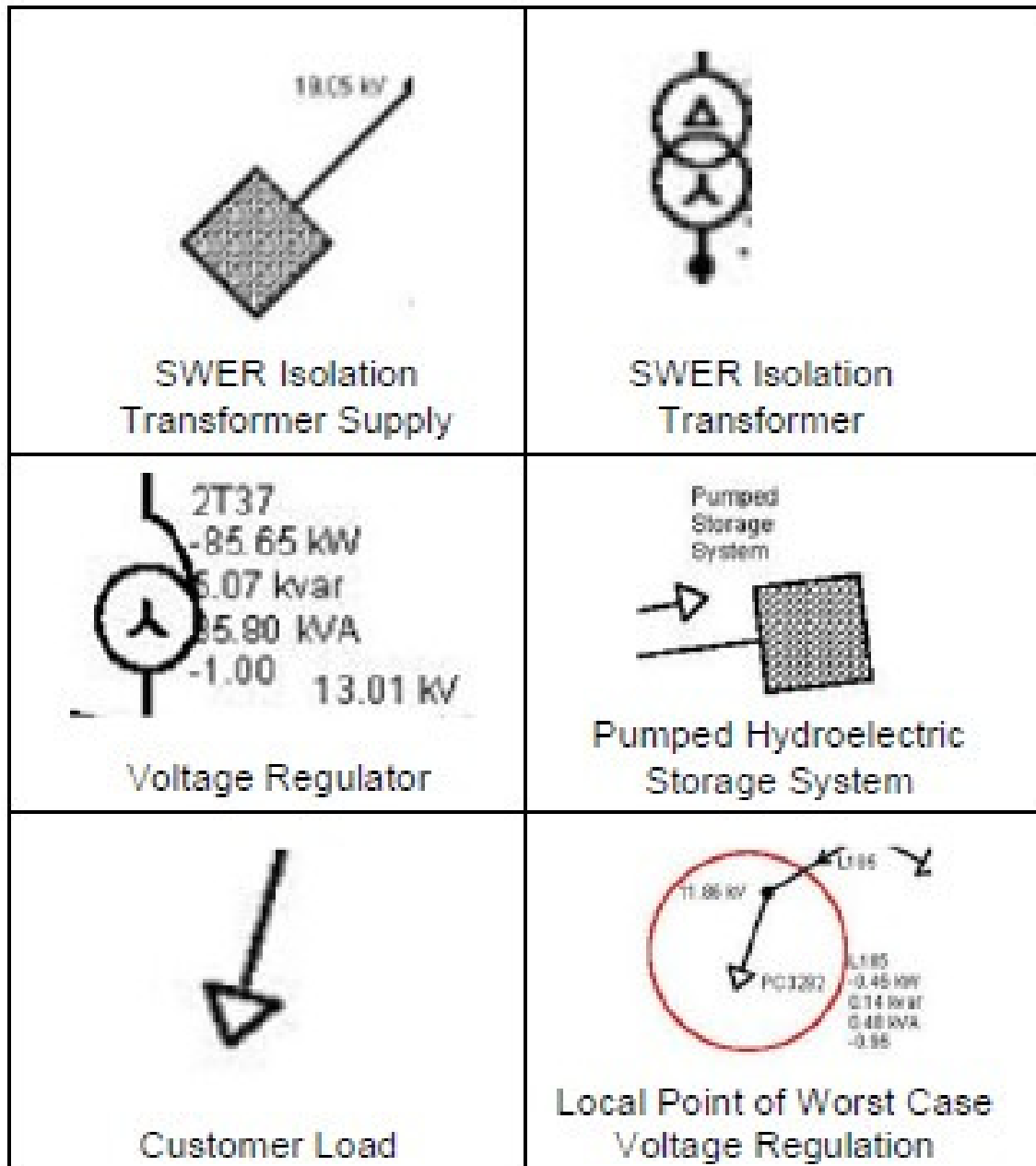


Figure 27 - PSS Sincal Diagrammatic Network Model Symbols

## 5.4. Methodology

The following steps were followed to simulate the effects of a pumped hydroelectric storage scheme on the network:

- 1) A model of the Wambo Creek SWER network was loaded into PSS Sincal.
- 2) The impedance of the upstream network was entered into the model for the analysis
- 3) The simulation was run with no pumped hydroelectric storage system connected at 25% and 100% loading. The results were recorded
- 4) The simulation was run with the pumped hydroelectric storage system inserted into a number of locations within the network. Its effect on the worst network voltages at each location was observed.
- 5) The pumped hydroelectric storage system was placed at the optimum location in the network.
- 6) The model was run with the pumped hydroelectric storage system consuming 25KW of active power in pumping mode and the feeder at 25% loading. The results were recorded.
- 7) The model was run with the pumped hydroelectric storage system generating 25 kW of active power and the feeder at 100% loading. The results were recorded.
- 8) The model was run with the pumped hydroelectric storage system generating 25 kvar of reactive power and the feeder at 100% loading. The results were recorded.

Note that the 100% load used is the highest load recorded on the feeder as of May 2013 which was 280 kVA. The load representing the lightly loaded system which typically occurs late at night and early in the morning was taken as 25% of this value (70 kVA).



## 5.5. Results

The results of the network modelling are shown in the PSS Sincal load flow analysis diagrams shown in Appendix H to Appendix L. Key results are also summarised in Table 8 to Table 11.

Wambo Creek SWER Feeder Pumped Storage System Modelling Results					
Voltage Variation Across the Network at Constant Load					
Test Description	Regulator Tap Position	Voltage at Lowest Voltage Node (kV)	Voltage at Highest Voltage Node (kV)	Node Voltage Variation Across Network (kV)	Node Voltage Variation Reduction Across Network Due to PHS (kV)
100% Load Without PHS	16	9.52	12.21	2.69	0.56
100% Load With PHS	16	10.21	12.34	2.13	
25% Load Without PHS	7	12.37	13.05	0.68	0.51
25% Load With PHS	8	11.83	13.01	1.18	

Table 8 - Voltage Variation across the Network at Constant Load

Wambo Creek SWER Feeder Pumped Storage System Modelling Results		
Voltage Variation Due to Varying Load at the Worst Case Node		
Test Description	Voltage Variation (kV)	Voltage Variation Reduction (kV)
100% to 25% Load Without Pumped Storage System	2.85	1.23
100% to 25% Load With Pumped Storage System	1.62	

Table 9 - Voltage Variation Due to Varying Load at the Worst Case Node

Wambo Creek SWER Feeder Pumped Storage System Modelling Results			
Isolation Transformer Secondary Load Reduction Due to PHS			
Test Description	Regulator Tap Position	Isolation TF Secondary Load (kVA)	Isolation TF Secondary Load Difference Due to PHS (kVA)
100% Load Without PHS	16	281.26	26.69
100% Load With PHS	16	254.57	
25% Load Without PHS	7	68.92	27.26
25% Load With PHS	8	96.18	

Table 10 - Isolation Transformer Secondary Load Reduction Due to PHS

Wambo Creek SWER Feeder Pumped Storage System Modelling Results	
Active & Reactive Power Injection Comparison - Effect on Network Voltage	
Test Description	Voltage at Lowest Voltage Node (kV)
100% Load Without Pumped Storage	9.52
100% Load With Pumped Storage System @ 25kW	10.21
100% Load With Pumped Storage System @ 25kVAr	9.78

Table 11 - Active & Reactive Power Injection Comparison - Effect on Network Voltage

## 5.6. Conclusions From Network Modelling

### 5.6.1. Assessment Against Key Performance Criteria

A large amount of data was produced by the PSS Sincal network model. However, the following key performance criteria were selected to quantify the effectiveness of the pumped hydroelectric storage system in improving network voltage and capacity constraints:

#### Voltage Variation across the Network

As shown in Table 8, the voltage variation across the network was reduced by 0.56 kV (0.044 pu) at 100% load and 0.51 kV (0.040 pu) at 25% load due to the installation of the pumped hydroelectric storage system. Reduced voltage variation across the network makes it possible to supply more load without using other augmentation and voltage regulation techniques.

#### Minimum Network Voltage

As shown in Table 8, the minimum network voltage experienced by the network was increased from 9.52 kV (0.75 pu) to 10.21 kV (0.80 pu) due to the pumped hydroelectric storage system. This will help to negate the need to compensate for this voltage drop using other augmentation and voltage regulation techniques.

#### Voltage Variation at the Worst Case Node

As shown in Table 9, with the load varying between 25% and 100% on the SWER feeder, the voltage at the worst case node varied by 2.85 kV (0.22 pu) without pumped hydroelectric storage and 1.62 kV (0.13 pu) with pumped hydroelectric storage. The pumped hydroelectric storage system was therefore responsible for a reduction in the voltage swing of 1.23 kV (0.10 pu).

This result shows that the pumped hydroelectric storage system will allow more load to be supplied by the SWER line by reducing nodal voltage variations to within the limits defined by the national electricity rules. This voltage variation reduction could be improved with the addition of a voltage regulator, however their tap changers respond too slowly to sudden load rejection which prohibits their use in some applications (see Section 3.2.8.3 for details).

#### SWER Isolation Transformer Peak Load

As shown in Table 10 the peak load of the SWER isolation transformer supplying the line reduced from 281.26 kVA to 254.57 kVA with the addition of the pumped hydroelectric storage scheme. This is a 26.69 kVA (0.13 pu) load reduction. The peak load is still in excess of the transformer's rating however it has improved the situation which will reduce the likelihood of transformer failure.

### Summary

The network modelling completed as part of this project shows that of all the key performance criteria assessed, all showed a substantial improvement due to the installation of the pumped hydroelectric storage system. This shows that a pumped hydroelectric storage system is effective in improving network capacity and voltage constraints on a SWER feeder.

#### **5.6.2. Active Power Vs Reactive Power Injection**

The final component of the network modelling was completed to compare the effectiveness of injecting active power to the effectiveness of injecting reactive power when attempting to improve the voltage drop across a fully loaded SWER feeder. The following scenarios were simulated:

- SWER feeder at 100% load, no power injected
- SWER feeder at 100% load, 25 kVA of active power injected
- SWER feeder at 100% load, 25 kvar of reactive power injected

The results of this simulation are shown in Table 11. A 0.69 kV (0.054 pu) voltage improvement can be observed with the injection of active power whereas only a 0.26 kV (0.020 pu) voltage improvement can be observed with the injection of reactive power. This highlights one of the advantages of installing a pumped hydroelectric storage when compared to some other techniques used to improve network voltage regulation such as the installation of a STATCOM.

## **6. Conclusions & Recommendations**

### **6.1. Achievement of the Project Objectives**

All of the project's objectives have been successfully achieved. This includes an investigation of electrical energy storage media and their suitability to the SWER network voltage regulation application. The results of this investigation can be found in Chapter 2 of this dissertation.

Background information relating to hydroelectric systems and SWER networks, with a focus on Ergon Energy's SWER network were researched. This background information can be found in Chapter 3 of this dissertation. The project also successfully analysed the current problems and conventional solutions employed to fix these problems within Ergon Energy's SWER network. This analysis can be found in Section 3.2.8 of this dissertation.

Key mechanical and electrical components of a pumped hydroelectric storage scheme for a typical rural application were successfully designed. The design was for a 25 kW 100 kWh system aimed at improving the voltage regulation on a SWER feeder. This design is documented in Chapter 4 of this dissertation.

The effects of a 25 kW pumped hydroelectric storage scheme on an Ergon Energy SWER feeder were modelled using PSS Sincal modelling software. Details of this modelling are shown in Section 5 of this dissertation.

Finally, this project determined whether it is feasible to implement a pumped hydroelectric storage scheme on a rural SWER line to improve network voltage regulation. This feasibility took into account the research and design components of the entire project. This feasibility is discussed in Section 6.6 of this dissertation.

## **6.2. Comparison With Other Storage Mediums**

It can be concluded that if an upper and lower reservoir exists near the location of a SWER network voltage constraint, pumped hydroelectric storage is superior to the other storage media studied for the SWER network voltage support application. This is because its capacity does not decline with age, the number of times it is cycled or the depth to which it is discharged. Pumped hydroelectric storage is also a reliable, commercially available technology which has a high efficiency and is capable of storing energy for a long duration.

## **6.3. Effectiveness at Improving Network Voltage Constraints**

The modelling completed as part of this project showed that installing a pumped hydroelectric storage system on a SWER feeder is an effective method of improving SWER network voltage regulation. The capacity of the SWER feeder was substantially increased as a result of installing the pumped hydroelectric storage system. The modelling also showed that the ability of pumped hydroelectric storage schemes to inject active as well as reactive power increased their effectiveness at improving the network voltage.

## **6.4. System Design**

It can be concluded that the inverter style pumped hydroelectric storage design is the preferred design for this application because it can supply reactive power to the network without depleting precious water reserves.

## **6.5. Reservoir Requirements**

A 100 kWh storage capacity was used for this project to provide a useful comparison to the GUSS units which are currently installed throughout Ergon Energy's SWER network (see Section 3.2.8.4 for details). This project showed that the upper and lower reservoirs required for a 100 kWh pumped hydroelectric storage system would be 25.9m long by 25.9m wide by 2m deep with 38m of head height. Although not in abundance, unused reservoirs with these dimensions still exist in the rural setting where SWER feeders are located. Possible locations include disused open pit mines and farming dams.

## **6.6. Feasibility**

The research and design completed as part of this project has shown that it is technically feasible to install a pumped hydroelectric storage system to improve voltage regulation on a SWER feeder.

Pumped hydroelectric storage technology is already used on large scale plants connected to transmission networks, however it has never been implemented on a distribution network. This project has shown that the engineering requirements of installing a pumped hydroelectric storage system are comparable to other techniques currently employed to improve SWER network voltage constraints if an upper and lower reservoir already exist. The construction of the reservoirs would make pumped hydroelectric storage unfeasible for small scale projects.

It can therefore be concluded that the pumped hydroelectric storage option should only be considered for this application if the upper and lower reservoir already exist with minimal civil works required. A detailed options analysis including the pumped storage option should be completed when addressing a network voltage constraint.

## **6.7. Recommendations / Further Work**

It is recommended that a full detailed design of the inverter based pumped hydroelectric storage system is completed. The system should then be trialled on the network. If the trial is successful a standard product should be developed in consultation with equipment manufactures to expedite and simplify future use of this technology.

After the successful completion of the trial, it is recommended that engineers perform a basic search for suitable pumped hydroelectric storage reservoirs in the area where a SWER network voltage constraint exists. If suitable storage reservoirs are located, the pumped hydroelectric storage solution should be included in their technical options assessment and financial analysis. A site assessment guideline should also be developed to assist engineers in determining whether reservoirs are suitable for a pumped hydroelectric storage system.

Further work should also be completed to collate a database of disused open pit mines and other reservoirs in Queensland. The database should include an assessment of their suitability to pumped hydroelectric storage technology and their proximity to a SWER network. This database will assist with the development of future projects.

## References

- ABC. (2013, December 12). *Qld Power Prices Set For Hike*. Retrieved from ABC News: <http://www.abc.net.au/news/2013-12-11/qld-power-prices-set-for-hike/5149394>
- AEMC. (2013, March 22). *Household Electricity Price Trends*. Retrieved from Australian Energy Market Commission: <http://www.aemc.gov.au/media/docs/Fact-Pack---AEMC-Price-Trends-Report-53b9d522-662f-467e-bf8a-b74d69d696d7-0.PDF>
- AEMO. (2014). *Australian Energy Market Operator*. Retrieved March 23, 2014, from Australian Energy Market Operator: <http://www.aemo.com.au/Electricity>
- Arefi, A., & Ledwich, G. (2013). Maximum Loadability Achievements in SWER Networks Using Optimal Sizing and Locations of Batteries. *Power Engineering Conference (AUPEC) Australasian Universities* (pp. 1-6). Hobart: IEEE.
- Australian Energy Market Commission. (2014, August 1). *National Electricity Rules Version 64*. Retrieved from Australian Energy Market Commission: <http://www.aemc.gov.au/energy-rules/national-electricity-rules/current-rules>
- Carpenter, G. L., Roden, S. M., & Savant, C. (1987). *Electronic Circuit Design - An Engineering Approach*. California: The Benjamin/Cummings Publishing Company, Inc.
- Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, pp. 291-329.
- EIA. (2013, July 8). *U.S. Energy Information Administration*. Retrieved from Today in Energy: <http://www.eia.gov/todayinenergy/detail.cfm?id=11991>
- Electricity Authority of NSW. (1968). *High Voltage Earth Return Distribution For Rural Areas*. Electricity Authority of NSW.
- Emerson. (2014, July 30). *Emerson Industrial Automation*. Retrieved July 30, 2014, from Emerson Industrial Automation: <http://www.emersonindustrial.com/en-EN/Electric-Power-Generation/Pages/home.aspx>
- Ergon Energy SWER Improvement Group. (2012). *Ergon Energy SWER Network Management Strategy*. Townsville: Ergon Energy.
- Ergonomics for Computer Workstation*. (2014, June 23). Retrieved from Ergonomics-Info.com: <http://www.ergonomics-info.com/index.html>

- Estrada, G. (2014, January 3). *Energy Project Slated for County*. Retrieved from The Ely Times: <http://www.elynews.com/2014/01/03/energy-project-slated-county/>
- Gilbert Gilkes & Gordon. (2014, July 30). *Hydropower*. Retrieved July 30, 2014, from Gilbert Gilkes & Gordon: <http://www.gilkes.com/Hydropower>
- Guinane, A., Shafiuallah, G., Amanullah, M., & Harvey, B. E. (2012). Voltage Fluctuations in PV Penetration on SWER Networks - A Case Study for Regional Australia. *Power and Energy Society General Meeting* (pp. 1 - 6). San Diego: IEEE.
- Helwig, A., & Ahfock, T. (2013). Long-life Nickel Iron Battery Functionality / Cost Comparison for Peak Demand Swer Network Voltage Support Application. *Australasian Universities Power Engineering Conference, IEEE* (pp. 1 - 6). Hobart: AUPEC.
- IHA. (2014, March 26). *International Hydropower Association*. Retrieved from International Hydropower Association: <http://www.hydropower.org/>
- Kashem, M., & Ledwich, G. (2005). Energy injection by distributed generation for enhancement of voltage profile in SWER systems. *Australian Journal of Electrical & Electronics Engineering*, 273-281.
- Louis, A. (2013). *Grid Utility Support System - Final Report Phase 1*. Cairns: Ergon Energy.
- Majellan Power. (2014, July 30). *Magellan Power*. Retrieved July 30, 2014, from Magellan Power: <http://www.magellanpower.com.au/>
- Pearen, C. (2003, October). Brushless Alternators. *Home Power*, pp. 68-71.
- Penche, C. (1998). *Laymans's Guidebook on How to Develop a Small Hydro Site 2nd Edition*. European Commission.
- Power Quality World*. (2014, April 26). Retrieved from Power Quality World: <http://www.powerqualityworld.com/>
- R.W.Jarrett, Maung Than Oo, D., & Harvey, B. (2012). An Investigation Into The Use Of Four Quadrant Inverter Devices For Voltage And Var Support On SWER Systems. *Universities Power Engineering Converence (AUPEC), 2012 22nd Australasian* (pp. 1-7). Bali: IEEE.
- RS Components. (2014, October 3). *Electronics Components, Power & Connectors*. Retrieved from RS Components: <http://au.rs-online.com/web/p/aluminium-capacitors/7740916/?searchTerm=774-0916>
- Semikron. (2014, September 5). *Semikron*. Retrieved from Bridge Rectifier Modules: <http://www.semikron.com/products/product-classes/bridge-rectifier-modules.html>



SLAC National Accelerator Laboratory. (2013, April 24). *New Battery Design Could Help Solar and Wind Energy Power the Grid*. Retrieved from SLAC National Accelerator Laboratory: <https://www6.slac.stanford.edu/news/2013-04-24-polysulfide-flowbattery.aspx>

*Wivenhoe Power Station Fact Sheet*. (2014, February 17). Retrieved from CS Energy Web Site: <http://www.csenergy.com.au/userfiles/file/Wivenhoe%20Power%20Station%20fact%20sheet%20-%20April%202013.pdf>

Zillmann, M., Ruifeng, Y., & Saha, T. (2011). Regulation of distributed network voltage using dispersed battery storage systems: A case study of a rural network. *Power and Energy Society General Meeting* (pp. 1-8). Dan Diego: IEEE.

# Appendix A: Project Specification

## Topic:

Investigation of Energy Storage Media to Improve Network Voltage Regulation

**Supervisor:** Dr Leslie Bowtell

**Sponsor:** Ergon Energy

## Project Aim

The purpose of the project is to investigate whether it is feasible to implement a pumped hydroelectric storage scheme on a rural Single Wire Earth Return (SWER) line to improve network voltage regulation.

## Programme

ISSUE B: 20<sup>th</sup> April 2014

1. Investigate electrical energy storage media and their suitability to the SWER network voltage regulation application.
2. Research background information relating to the design, construction and operation of hydroelectric systems.
3. Research background information relating to SWER networks.
4. Research background information relating to Ergon Energy's SWER network.
5. Analyse the current problems and conventional solutions employed to fix these problems within Ergon Energy's SWER network.
6. Design a pumped hydroelectric storage scheme for a typical rural application.
7. Model the effects of a pumped hydroelectric storage scheme on an Ergon Energy SWER feeder.
8. Analyse the results and determine whether it is feasible to implement a pumped hydroelectric storage scheme on a rural SWER line to improve network voltage regulation.
9. Submit an academic dissertation on the research.

As Time Permits:

1. Perform an economic analysis on the pumped hydroelectric storage solution and compare this with conventional solutions.

## Appendix B: Brushless Generator Data Sheet Extract

(Emerson, 2014)



### Low Voltage alternators - 4 pole LSA 42.3

25 to 60 kVA - 50 Hz / 31.5 to 75 kVA - 60 Hz

Electrical and mechanical data

4802 es - 2014.01 / e

## Low Voltage alternators 4 pole 3-phase **PARTNER**

### LSA 42.3

25 to 60 kVA - 50 Hz / 31.5 to 75 kVA - 60 Hz

#### SPECIALLY ADAPTED TO APPLICATIONS

The LSA 42.3 alternator is designed to be suitable for typical generator applications, such as: backup, marine applications, rental, telecommunications, etc.

#### COMPLIANT WITH INTERNATIONAL STANDARDS

The LSA 42.3 alternator conforms to the main international standards and regulations:

- IEC 60034, NEMA MG 1.22, ISO 8528-3, CSA / UL on request, marine regulations, etc.

It can be integrated into a CE marked generator.

The LSA 42.3 is designed, manufactured and marketed in an ISO 9001 environment and ISO 14001.

#### TOP OF THE RANGE ELECTRICAL PERFORMANCE

- Class H insulation.
- Standard 12 wire re-connectable winding, 2/3 pitch, type no. 6.
- Voltage range:
  - 50 Hz: 220 V - 240 V and 380 V - 415 V (440 V)
  - 60 Hz: 208 V - 240 V and 380 V - 480 V
- High efficiency and motor starting capacity.
- Other voltages are possible with optional adapted windings:
  - 50 Hz: 440 V (no. 7), 500 V (no. 9), 690 V (n°10)
  - 60 Hz: 380 V and 416 V (no. 8), 600 V (no. 9)
- R 791 interference suppression conforming to standard EN 55011 group 1 class B standard for European zone (CE marking).

#### REINFORCED MECHANICAL STRUCTURE USING FINITE ELEMENT MODELLING

- Compact rigid assembly to better withstand generator vibrations.
- Steel frame.
- Aluminium flanges and shields.
- Two-bearing and single-bearing versions designed to be suitable for commercially-available heat engines.
- Half-key balancing two bearing.
- Permanently greased bearings (20 000h).
- Direction of rotation : clockwise and anti-clockwise (without derating).

#### EXCITATION AND REGULATION SYSTEM SUITED TO THE APPLICATION

Excitation system				Regulation options				
Voltage regulator	SHUNT	AREP	PMG	Current transformer for paralleling	Mains paralleling	3-phase sensing	3-phase sensing for mains paralleling unbalanced	Remote voltage potentiometer
R220	Std	-	-	-	-	-	-	-
R438	-	Std	Std	C.T.	R726*	R731*	R734*	√
R450	Option	Option	Option	C.T.	R726*	R731*	R734*	√
D510C*	Option	Option	Option	C.T.	included	included	contacter factory	√

\* Steel terminal box mounting only

√: Possible mounting

#### COMPACT AND DESIGN TERMINAL BOX

- Easy access to the AVR (lid) and to the connections.
- 8 way terminal block for reconnecting the voltage.
- Predrilled holes for cable gland.
- Steel terminal box in option.

#### PROTECTION SYSTEM SUITED TO THE ENVIRONMENT

- The LSA 42.3 is IP 23.
- Standard winding protection for clean environments with relative humidity ≤ 95%, including indoor marine environments.
- Options:
  - filters on air inlet : derating 5%,
  - filters on air inlet and air outlet (IP 44) : derating 10%,
  - winding protection for harsh environments and relative humidity greater than 95%,
  - space heaters,
  - thermal protection for stator windings,
  - height fixing : H = 225 mm (option) with the order.



## Appendix C: Bridge Rectifier Specifications

(Semikron, 2014)

### SKD 160



**SEMIPONT® 4**

#### Power Bridge Rectifiers

**SKD 160**

#### Features

- Robust plastic case with screw terminals
- Large, isolated base plate
- Blocking voltage up to 1800 V
- High surge currents
- Three phase bridge rectifier
- Easy chassis mounting
- UL recognized, file no. E 63 532

#### Typical Applications\*

- Three phase rectifiers for power supplies
- Input rectifiers for variable frequency drives
- Rectifiers for DC motor field supplies
- Battery charger rectifiers

1) Available in limited quantities

2) Mounted on a painted metal sheet of min. 250 x 250 x 1 mm;

$R_{th(c-a)} = 1,8 \text{ K/W}$

$V_{RSM}$ V	$V_{RRM}, V_{DRM}$ V	$I_D = 160 \text{ A}$ (full conduction) ( $T_c = 100^\circ \text{C}$ )
800	800	SKD 160/08
1200	1200	SKD 160/12
1400	1400	SKD 160/14
1600	1600	SKD 160/16
1800	1800	SKD 160/18 <sup>1)</sup>


Symbol	Conditions	Values	Units
$I_D$	$T_c = 85^\circ \text{C}$ $T_a = 45^\circ \text{C}$ ; chassis <sup>2)</sup> $T_a = 45^\circ \text{C}$ ; P1/200 $T_a = 35^\circ \text{C}$ ; P1/120F $T_a = 35^\circ \text{C}$ ; P3/120F	205 30 75 145 146	A A A A A
$I_{FSM}$	$T_{vj} = 25^\circ \text{C}$ ; 10 ms $T_{vj} = 150^\circ \text{C}$ ; 10 ms	1800 1500	A A
$\hat{I}_T$	$T_{vj} = 25^\circ \text{C}$ ; 8,3 ... 10 ms $T_{vj} = 150^\circ \text{C}$ ; 8,3 ... 10 ms	16200 11200	A <sup>2</sup> s A <sup>2</sup> s
$V_F$	$T_{vj} = 25^\circ \text{C}$ ; $I_F = 300 \text{ A}$	max. 1,65	V
$V_{(TO)}$	$T_{vj} = 150^\circ \text{C}$	max. 0,85	V
$r_T$	$T_{vj} = 150^\circ \text{C}$	max. 3	mΩ
$I_{RD}$	$T_{vj} = 25^\circ \text{C}$ ; $V_{DO} = V_{DRM}$ ; $V_{RD} = V_{RRM}$ $T_{vj} = 150^\circ \text{C}$ ; $V_{RD} = V_{RRM}$	max. 0,5 6	mA mA
$R_{th(j-c)}$	per diode total	0,65 0,11	K/W K/W
$R_{th(c-a)}$	total	0,03	K/W
$T_{vj}$		- 40 ... + 150	°C
$T_{stg}$		- 40 ... + 125	°C
$V_{isol}$	a. c. 50 Hz; r.m.s.; 1 s / 1 min.	3600 ( 3000 )	V
$M_s$	to heatsink	$5 \pm 15 \%$	Nm
$M_t$	to terminals	$5 \pm 15 \%$	Nm
m		270	g
Case		G 37	

# Appendix D: Capacitor Specifications

(RS Components, 2014)

## Epcos 15000 $\mu$ F $\pm$ 20 % 9 m $\Omega$ 400 V dc Clamp Mount Cylindrical Aluminium Capacitor





This image is representative of the product range

Price (ex. GST) Each

You are currently not logged in [Register](#) / [Log-In](#)

Qty	Unit Price
1	\$522.13
2	\$469.91

- [Click here to see more stock](#)
- [Industry standard packaging](#)
- [Lower prices](#)

In stock for delivery within 5 working days

Real time qty checker

1

Add

RS Stock No.

774-0916

Manufacturer

[Epcos](#)

Mfr. Part No.

B43456A9159M000

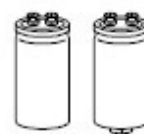
RoHS Status

[Compliant](#)

Customer reviews

(0) [Add a review](#)




**Specifications and characteristics in brief**

Rated voltage $V_R$	350 ... 550 V DC														
Surge voltage $V_S$	$1.10 \cdot V_R$														
Rated capacitance $C_R$	560 ... 18000 $\mu\text{F}$														
Capacitance tolerance	$\pm 20\% \triangleq M$														
Leakage current $I_{\text{leak}}$ (20 °C, 5 min)	$I_{\text{leak}} \leq 0.020 \mu\text{A} \cdot \left( \frac{C_R}{\mu\text{F}} \cdot \frac{V_R}{V} \right)^{0.85} + 4 \mu\text{A}$														
Self-inductance ESL	d = 51.6 mm: approx. 15 nH d $\geq$ 64.3 mm: approx. 20 nH Capacitors with low-inductance design: d $\geq$ 64.3 mm: approx. 13 nH														
Useful life 85 °C; $V_R$ ; $I_{AC,R}$ 40 °C; $V_R$ ; $1.5 \cdot I_{AC,R}$	350 V ... 450 V > 12000 h > 250000 h	500 V ... 550 V > 8000 h > 240000 h	Requirements: $\Delta C/C \leq \pm 30\%$ of initial value ESR $\leq 3$ times initial specified limit $I_{\text{leak}} \leq$ initial specified limit												
Voltage endurance test 85 °C; $V_R$	2000 h		Post test requirements: $\Delta C/C \leq \pm 10\%$ of initial value ESR $\leq 1.3$ times initial specified limit $I_{\text{leak}} \leq$ initial specified limit												
Vibration resistance test	To IEC 60068-2-6, test Fc: Frequency range 10 ... 55 Hz, displacement amplitude 0.75 mm, acceleration max. 10 g, duration $3 \times 2$ h. Capacitor mounted by its body which is rigidly clamped to the work surface.														
Characteristics at low temperature	Max. impedance ratio at 100 Hz	<table><tr><td><math>V_R</math></td><td><math>\leq 400 \text{ V}</math></td><td><math>\geq 450 \text{ V}</math></td><td>500 ... 550 V</td></tr><tr><td><math>Z_{-25^\circ\text{C}} / Z_{20^\circ\text{C}}</math></td><td>3</td><td>4</td><td>3</td></tr><tr><td><math>Z_{-40^\circ\text{C}} / Z_{20^\circ\text{C}}</math></td><td>7</td><td>9</td><td>10</td></tr></table>	$V_R$	$\leq 400 \text{ V}$	$\geq 450 \text{ V}$	500 ... 550 V	$Z_{-25^\circ\text{C}} / Z_{20^\circ\text{C}}$	3	4	3	$Z_{-40^\circ\text{C}} / Z_{20^\circ\text{C}}$	7	9	10	
$V_R$	$\leq 400 \text{ V}$	$\geq 450 \text{ V}$	500 ... 550 V												
$Z_{-25^\circ\text{C}} / Z_{20^\circ\text{C}}$	3	4	3												
$Z_{-40^\circ\text{C}} / Z_{20^\circ\text{C}}$	7	9	10												
IEC climatic category	To IEC 60068-1: 40/085/56 (–40 °C/+85 °C/56 days damp heat test)														
Detail specification	Similar to CECC 30301-803, CECC 30301-807														
Sectional specification	IEC 60384-4														

**Ripple current capability**

Due to the ripple current capability of the contact elements, the following current upper limits must not be exceeded:

Capacitor diameter	51.6 mm	64.3 mm	76.9 mm	91 mm
$I_{AC,max}$	34 A	45 A	57 A	80 A

## Appendix E: Magellan Power Inverter Brochure

(Majellan Power, 2014)

AC RANGE

### INVERTERS (4 QUADRANT)

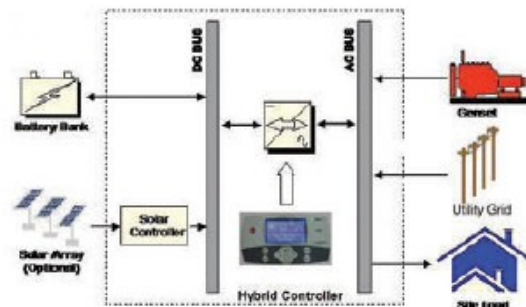
Inverter and Hybrid Power

#### PRODUCT FEATURES:

- Designed for harsh environment
- Bi-directional IGBT technology
- Pure Sinewave output
- Advanced DSP controls
- Suitable for use as stand-alone inverter and hybrid power
- High efficiency
- Isolated RS232 or RS485, Ethernet
- Modbus RTU, Modbus TCP, SNMP, Internal Webpage, DNP3 for inverter based products only
- Access facility software



Designed for high reliability and featuring microprocessor and DSP controls, the Magellan Power single-phase and three-phase Inverters are rated for continuous operation at full load. With full system remote diagnostics, monitoring and reporting via internet, along with integrated data and fault logging and settable software parameters, this equipment is ideal for hybrid power applications.





## TECHNICAL SPECIFICATIONS

General Specifications	
Operating Temperature	0 - 50°C (internal components industrially rated)
Maximum Humidity	95%, non-condensing
Cooling	Forced air with Temperature Controlled Cooling Fan
Enclosure	IP43 A1 (indoor)
Finish	Epoxy powder coated
Protections	
Circuit Breakers	DC Input; Load Output
Fault Monitoring	Inverter Over Voltage Monitoring; Inverter Over Load Monitoring; Inverter Current Limit Monitoring; Inverter Over Temperature Monitoring; Sensing Fault; Automatic Timed Restart on Fault Clear
DC Protections	DC Under Voltage Monitoring; DC Over Voltage Monitoring
Indications	
User Interface	128x64 Graphical Blue LCD with White LED Backlight; Membrane Keypad; Green Mains OK LED; Red Fault LED; Yellow Buzzer Mute LED
Monitored System Parameters	Battery Voltage, Current & Temperature; Inverter Voltage, Current & Temperature; Ambient Temperature, Transformer Temperature
Mimic Indications	Graphical overview of system and status; Power Flow direction
Communication	
Communication Ports	Isolated RS232 or USB Connector; Isolated RS485 Screw Terminal Connector; Ethernet 10-BASE-T RJ45 Connector
Communication Protocols	Modbus RTU (RS232/RS485); Modbus TCP (Ethernet); Distributed Network Protocol3 (Ethernet); Inbuilt Website (Ethernet); SNMP
Monitoring and Diagnostic Download Software	"Access Facility"; PC Software
Optional Alarm Relay Outputs	Inverter Fail Alarm; Battery Low Alarm; Common Alarm
Inverter Specifications	
Nominal Capacity	5kVA to 100 kVA
Overload Capacity	200% for 5 seconds; 150% for 30 seconds; >100% for 60 seconds
Nominal DC Voltage	110VDC – 400 VDC depending on model
Nominal Output AC	240V, 50Hz single phase, 415V, 50Hz, 3 Phase
DC Voltage Range	Nominal $\pm 12.5\%$
Output Voltage Regulation	$\pm 2\%$ Input and load variation
Output Frequency	50Hz $\pm 0.1$ Hz
Load Imbalance Capability	100%
Efficiency	>90% At rated load, nominal input voltage
Switching device	Trench IGBT
Voltage THD	<3% with resistive load

## Appendix F: Risk Assessment

RISK ASSESSMENT MATRIX						
	Probability					
Severity		Frequent A	Likely B	Occasional C	Seldom D	Unlikely E
Catastrophic	I	E	E	H	H	M
Critical	II	E	H	H	M	L
Marginal	III	H	M	M	L	L
Negligible	IV	M	L	L	L	L
E-Extremely High		H-High		M-Moderate		L-Low

### Project Risks 1:

Difficulties getting the network model to work in PSS SINICAL causing delay to the project						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
B	II	H	Discuss my impending PSS Sincal network analysis with a subject matter expert at work and ask them if they can be available to answer questions.	E	II	L

### Project Risks 2:

Work commitments not allowing me enough time to complete the project.						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
C	II	H	Discuss my project with my employer and make sure that I do not have too many projects allocated to me at work so that I can take annual leave if required.	E	II	L

Project Risks 3:

Computer failure causing lost data and delays to the project.						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
C	1	H	Backup the project every day.	E	I	M

Project Risks 4:

Subject matter experts reluctant to share information on new technologies.						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
A	II	H	Explain to the subject matter expert that a confidentiality agreement can be signed with the university if required so that the dissertation will not be published.	E	II	L

Project Risks 5:

Sickness preventing the on time completion of the project.						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
C	III	M	Maintain "slack" in the project schedule for such an event. Maintain an active and healthy lifestyle.	E	III	L

Health & Safety Risk 1:

Eye strain from long periods of computer use.						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
A	II	H	Take frequent rest breaks and focus on distant objects during these breaks.	E	II	L

Health & Safety Risk 2:

Injury as a result of a car accident while researching project.						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
C	I	H	Be alert when driving. Wear a seatbelt. Don't drive tired. Obey the road rules. Don't Drink and Drive.	E	I	M

Health & Safety Risk 3:

Body strain from incorrect posture						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
A	II	H	Ensure that my workstation is setup as shown in Figure 28.	E	II	L

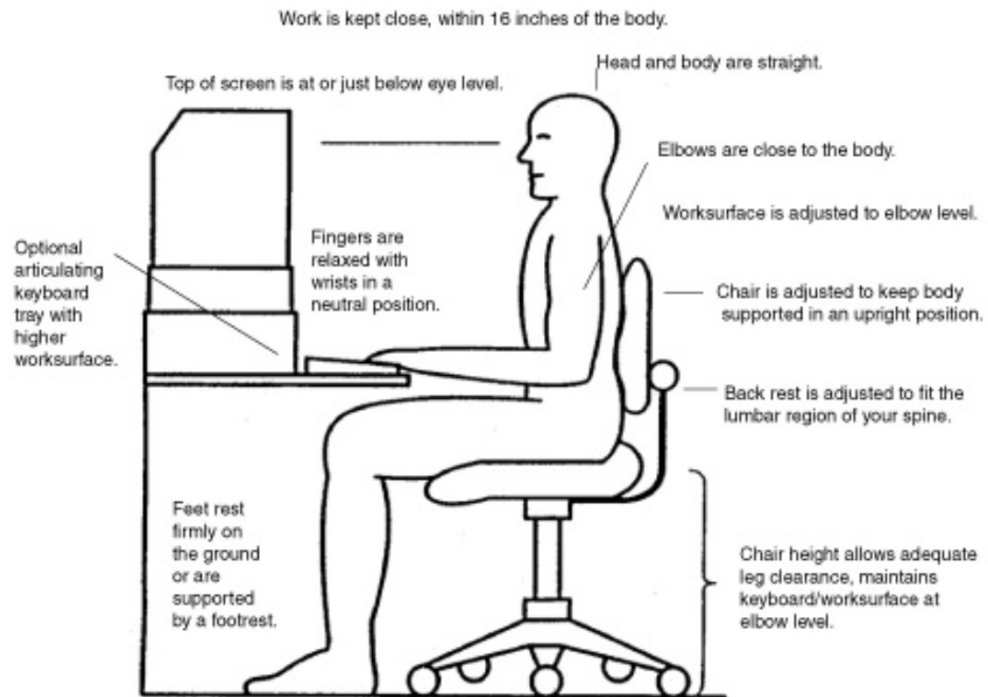


Figure 28 - Correct Workstation Setup (*Ergonomics for Computer Workstation*, 2014)

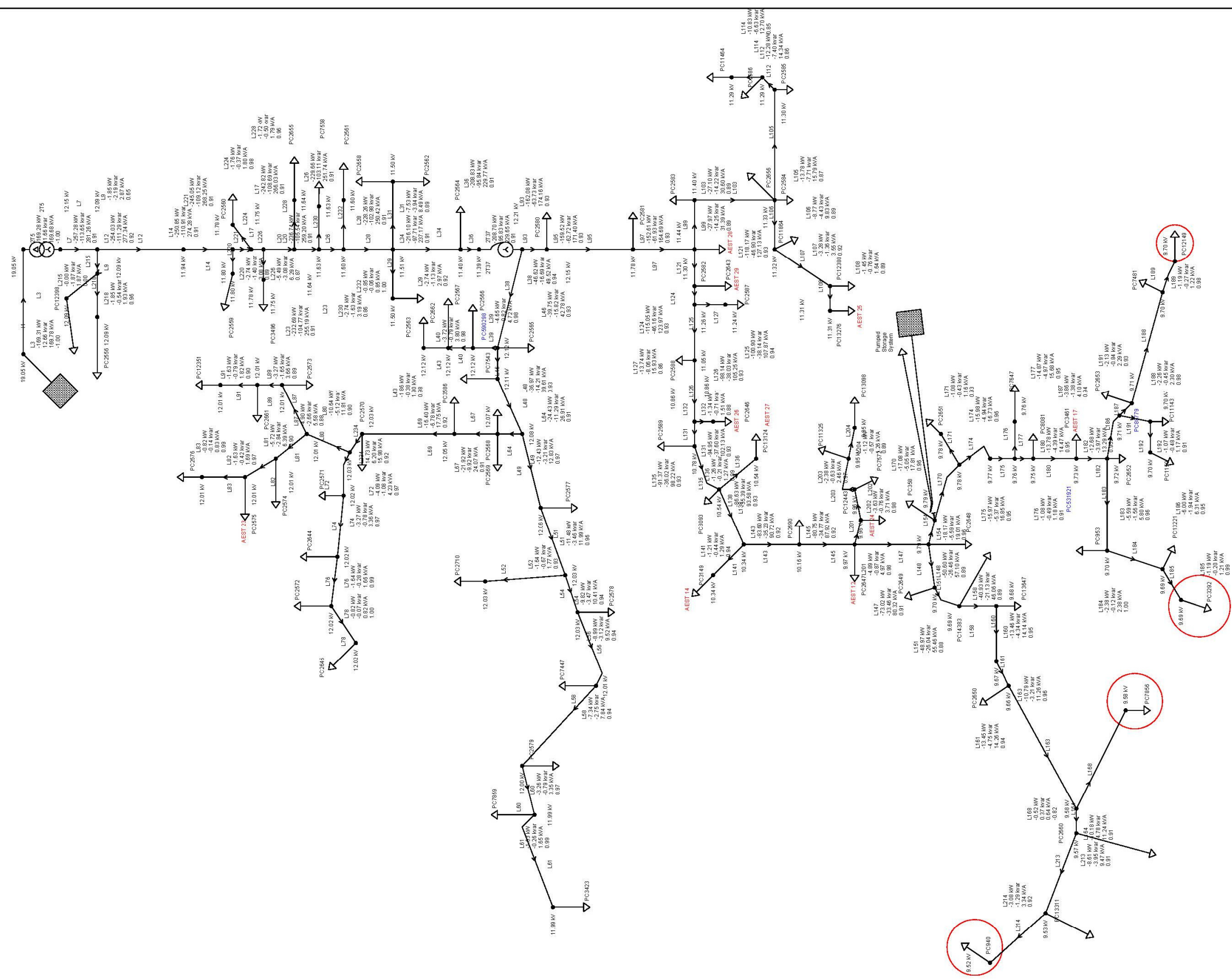
Health & Safety Risk 4:

Slips and trips while completing the project.						
Probability	Severity	Risk	CONTROL MEASURE	Revised Probability	Revised Severity	Revised Risk
B	III	H	Maintain good housekeeping both in the office and while doing research for the project. Wear appropriate footwear with adequate ankle support and grip.	D	III	M

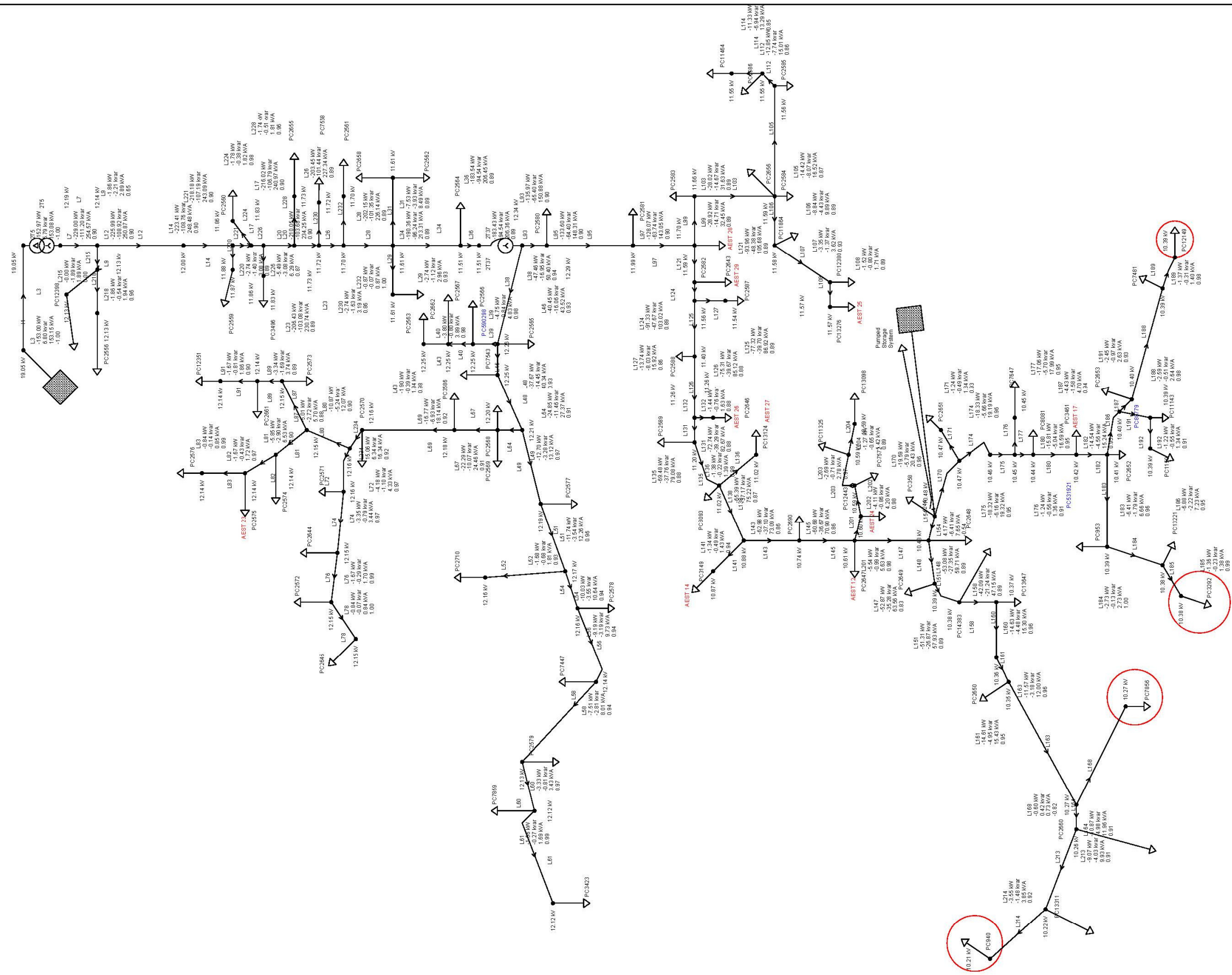
[illegible]



## Appendix H: Network Modelling Results – Wambo Creek SWER at 100% Load without Pumped Hydroelectric Storage

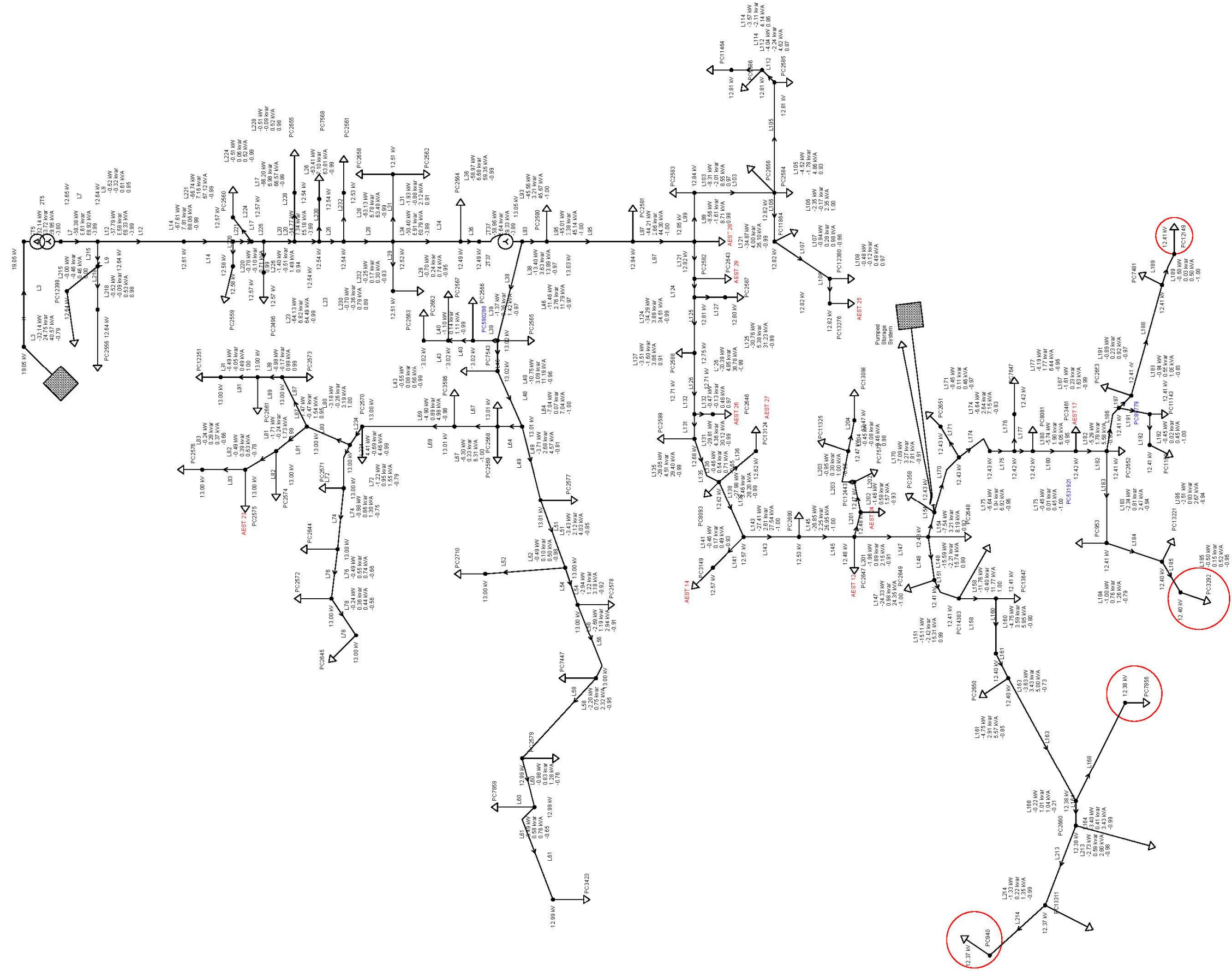


Appendix I: Network Modelling Results – Wambo Creek SWER at 100% Load with Pumped Hydroelectric Storage Generating 25 kVA





# Appendix J: Network Modelling Results – Wambo Creek SWER at 25% Load without Pumped Hydroelectric Storage



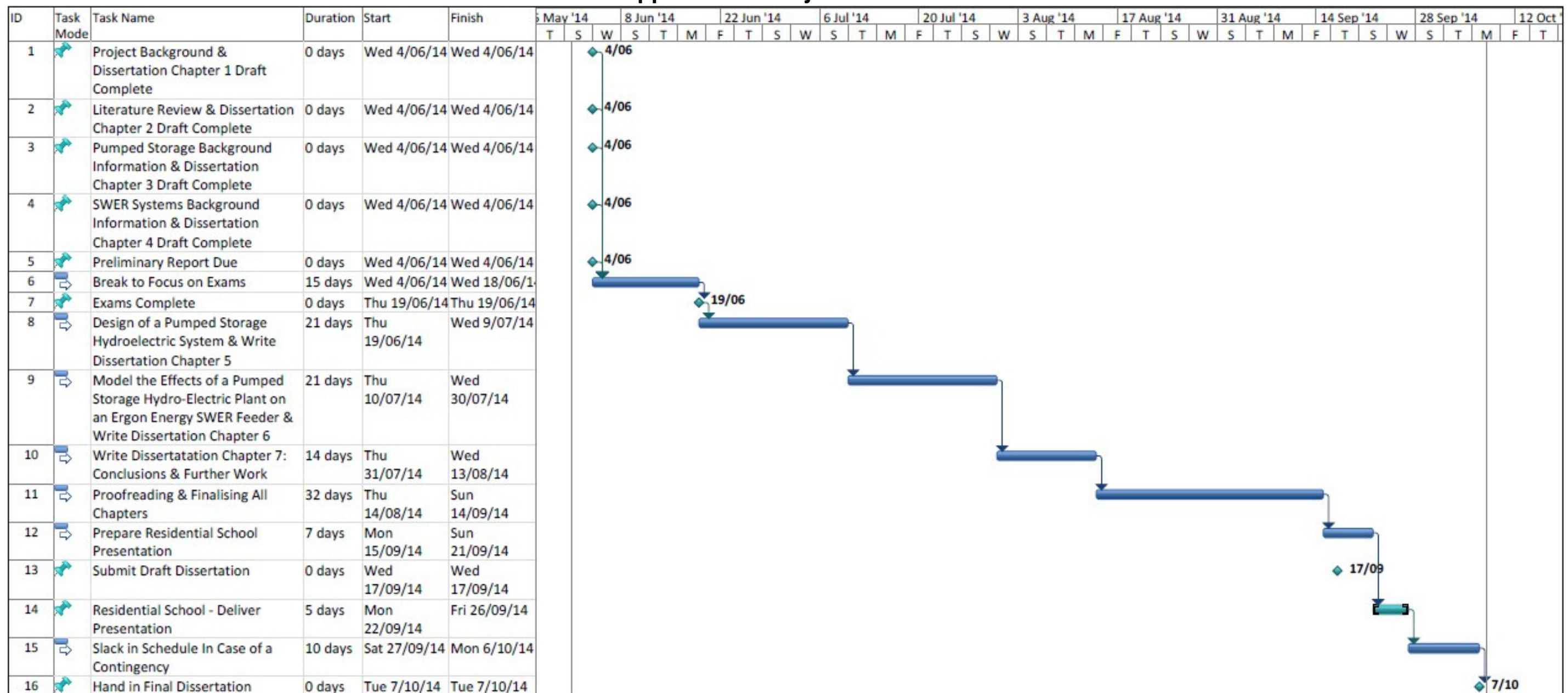








## Appendix M: Project Schedule



Project: msproj11 Date: Sat 17/05/14	Task		Project Summary		Inactive Milestone		Manual Summary Rollup		Deadline	
	Split		External Tasks		Inactive Summary		Manual Summary		Progress	
	Milestone		External Milestone		Manual Task		Start-only			
	Summary		Inactive Task		Duration-only		Finish-only			